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FLUME: A Computer Model for Estimating Flow Through Long-Throated Measuring Flumes

ABSTRACT

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A mathematical model has been developed for computing the stage discharge relation and energy losses for long-throated flumes and broad-crested weirs. The computer program presented in this publication can accommodate a wide variety of flume and channel shapes as well as many different input and output units. The program should handle a majority of the practical cases when open channel flow measurements are needed. This material greatly expands previously published programs and models.

KEYWORDS: broad-crested weirs, computer modeling, flow measurement, flumes, hydraulics, open channel flow, stage-discharge

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PREFACE

To effectively accomplish surface water management for irrigation distribution, municipal supply collection from watersheds, flood flow monitoring, or other purposes, it is important that the flow be accurately measured. Increasing and competing demands for water in our society are making efficient water use ever more necessary.

As a general policy, we recommend that water measuring capability be included on all new water projects and that existing water channels be retrofitted for water measurement as soon as practical.

Usually water measurements should be planned at all points where it can be reasonably established that the flow rate will affect management decisions. Thus water measurements should be planned at all bifurcations, or divisions in flow, within a distribution system canal, at all delivery outlets, and in the stream or river from which the flow is diverted.

For most open channel flows, we recommend critical-depth, long-throated measuring flumes, often shortened to long-throated flumes. The broad-crested weir also falls into the long-throated flume category when the approach is properly configured. Broad-crested weirs are particularly well adapted to irrigation canals. Other flume types are better adapted to natural streams.

These long-throated flumes should greatly expand the measuring choices and abilities of anyone concerned with water management and the efficient use of this valuable resource.

A computer program for predicting the flow through long-throated flumes has been developed for assistance in design, which is described herein. Because of the length and complexity of this program, a program listing is not included here. Copies of the program can be obtained by writing to the Authors and sending either a 9-track magnetic tape (returned in ASCII) or a 5¼ inch floppy disk (returned in MS DOS format).

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FLUME: A COMPUTER MODEL FOR ESTIMATING FLOW THROUGH LONG-THROATED MEASURING FLUMES

A.J. Clemmens, J.A. Replogle, and M.G. Bos[1]

1. INTRODUCTION

1.1 History and Advantages

Critical flow devices are often used to measure flow in open channels. A majority of these devices require laboratory calibrations because the discharge is not theoretically predictable, except through empirically derived coefficients. Two flow devices whose discharges can be theoretically predicted without the need for such coefficients are the long-throated flume and the modified broad-crested weir. Both have similar hydraulic properties.

The model for predicting discharge through long-throated flumes has resulted from over a century of development. The first laboratory and theoretical studies on critical-depth flumes were made by Belanger in 1849 and by Bazin in 1896. These studies were extended by Crump, (see Ackers et al. 1978) Inglis (1928), Jameson (1930), Fane (1927), and Palmer and Bowlus (1936), and others in the early part of this century. The theory and dimensional requirements for these flumes were well known by the 1950's (Wells and Gotaas 1958); however, calibration still required an empirical discharge coefficient. Theoretical predictions of flow were investigated by Ackers and Harrison (1963) and further refined by Replogle (1975). The stage-discharge theory of the current model is essentially that presented by Replogle, with minor improvements. Bos (1978) and Bos and Reinink (1981) developed a procedure for determining the required head loss across these flumes. This general theory was incorporated into the current model, with minor modifications to make it consistent with the procedures for the stage-discharge computations. This model supplies a complete prediction of flow patterns through long-throated, critical-flow flumes and weirs.

These flumes and weirs also have a number of other advantages:

1. Provided that critical flow occurs in the throat, a rating table can be calculated with an error of less than 2 percent in the listed discharge. The calculation can be made for any combination of a prismatic throat and an arbitrarily shaped approach channel.

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2. The throat, perpendicular to the direction of flow, can be shaped in such a way that the complete range of discharge can be measured accurately.

3. The head loss over the weir or flume, which is required in order to have a unique relationship between the upstream sill-referenced head, h_1, and the discharge, Q, is minimal.

4. This head-loss requirement can be estimated with sufficient accuracy for any of these structures placed in an arbitrary channel.

5. Because of their gradual converging transition three structures have little problem with floating debris.

6. Field observations have shown that the structure can be designed to pass sediment transported by channels that have subcritical flow. However, sedimentation can be a problem when sediment loads are excessively high or when the flume causes a significant reduction in the approach channel flow velocity.

7. Provided that the throat is horizontal in the direction of flow, a rating table can be produced which is based upon post-construction dimensions. Thus, an accurate rating table can be produced even if the flume is not constructed to the designed dimensions. Also, the throat may be re-shaped as needed according to changing site conditions.

8. Under similar hydraulic and other boundary conditions these weirs/flumes are usually the most economical of all structures for accurately measuring open channel flows.

Because of the above advantages, these flumes are useful for many flow measurement applications, particularly when the measurement device must have a minimal impact on existing flow and water surface elevations.

Further details on design and construction procedures, along with a number of standard size flumes and their ratings, are given in Bos et al. (1984). In this report, only the computer model, its operation and use, and the supporting theories are given.

1.2 Description

Long-throated flumes generally consist of five sections as shown in figure 1.1:

1. An approach channel, where the flow is stable and uniform so that the water level (and thus, energy head) can be determined accurately;

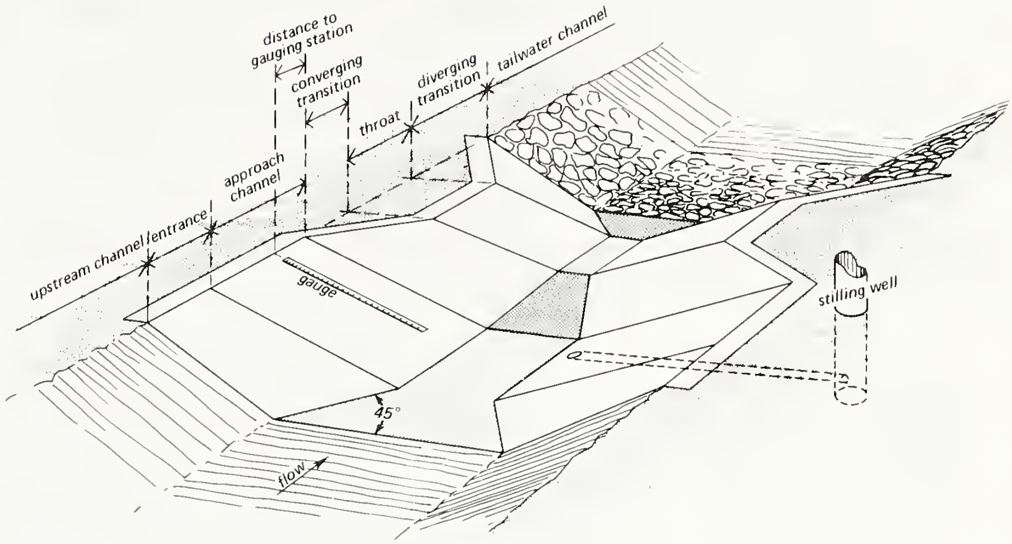

Figure 1.1.
General layout of a long-throated flume
(from Bos et al. 1984).

2. A converging transition that provides a smooth acceleration of flow with no discontinuities or flow separation;

3. A throat, where the flow is accelerated to critical flow;

4. A diverging transition to reduce the flow to an acceptable subcritical velocity and to recover energy;

5. A tailwater channel where the water level is controlled by flow downstream. Knowledge of this downstream water level is important to determine the level of the flume throat.

The major differences between long-throated flumes and broad-crested weirs stem from historical use of terminology rather than hydraulic properties. In this publication, both are considered long-throated flumes. The historical distinctions are shown in figure 1.2.

In general, both types of measuring structure cause a constriction in the flow. The design of these structures is based on providing enough of a constriction to produce critical flow over the full range of expected discharges while not producing too much of a head loss between the upstream water level and tailwater level.

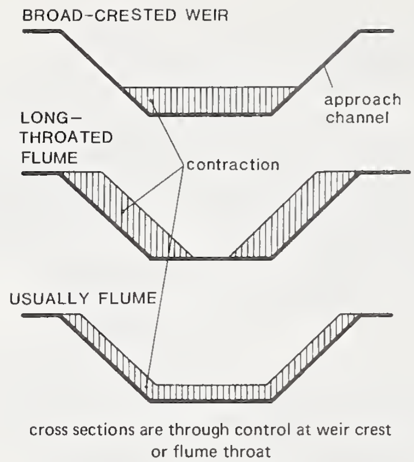

Figure 1.2.
Distinction between weir and flume (from Bos et al. 1984).

Figure 1.3 shows the general profile of flow through a long-throated flume. The subscripts 1 and 2 refer to conditions in the approach and tailwater channels, respectively. The reference elevation for energy levels is the bottom of the flume throat or crest of the weir sill, which will be referred to as the "sill reference". Thus, as shown, the actual water depth is described by y, and the sill-referenced depth is described by h. The difference between the two is the sill height, p. Also shown is the energy level, H, and the energy loss across the flume, ΔH. Limitations on profile dimensions shown in figure 1.3 are further discussed in chapters 2 and 3. Some additional limitations are introduced for the movable weirs to facilitate their use and to incorporate some practical considerations. These are shown in figure 1.4. Bos et al. (1984) have given additional details and options for movable weirs.

The control section is the approximate location of critical flow within the flume throat. The gauging (or head measurement) station is the location within the approach channel where the upstream head is measured. For critical flow devices, there is a unique relationship between the upstream head and discharge. The model presented here provides a good estimate of this relationship.

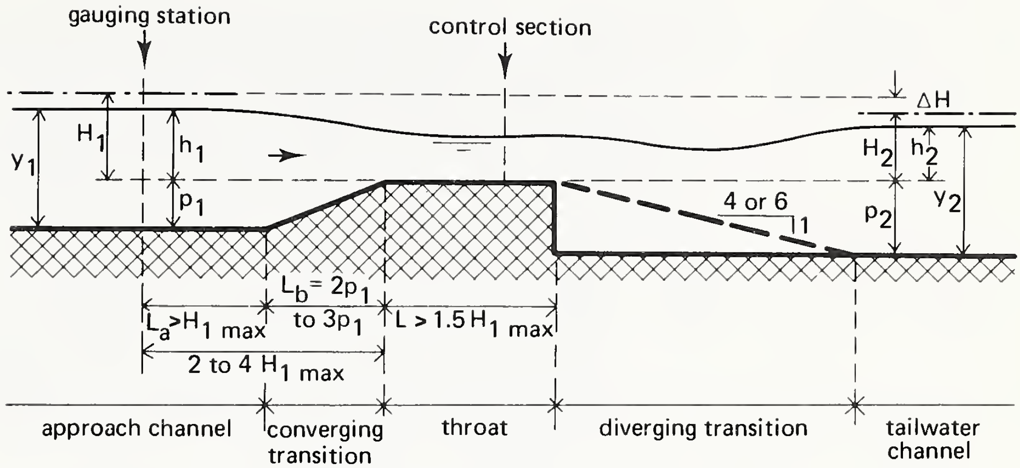

Figure 1.3.
Profile of flow through a long-throated flume.

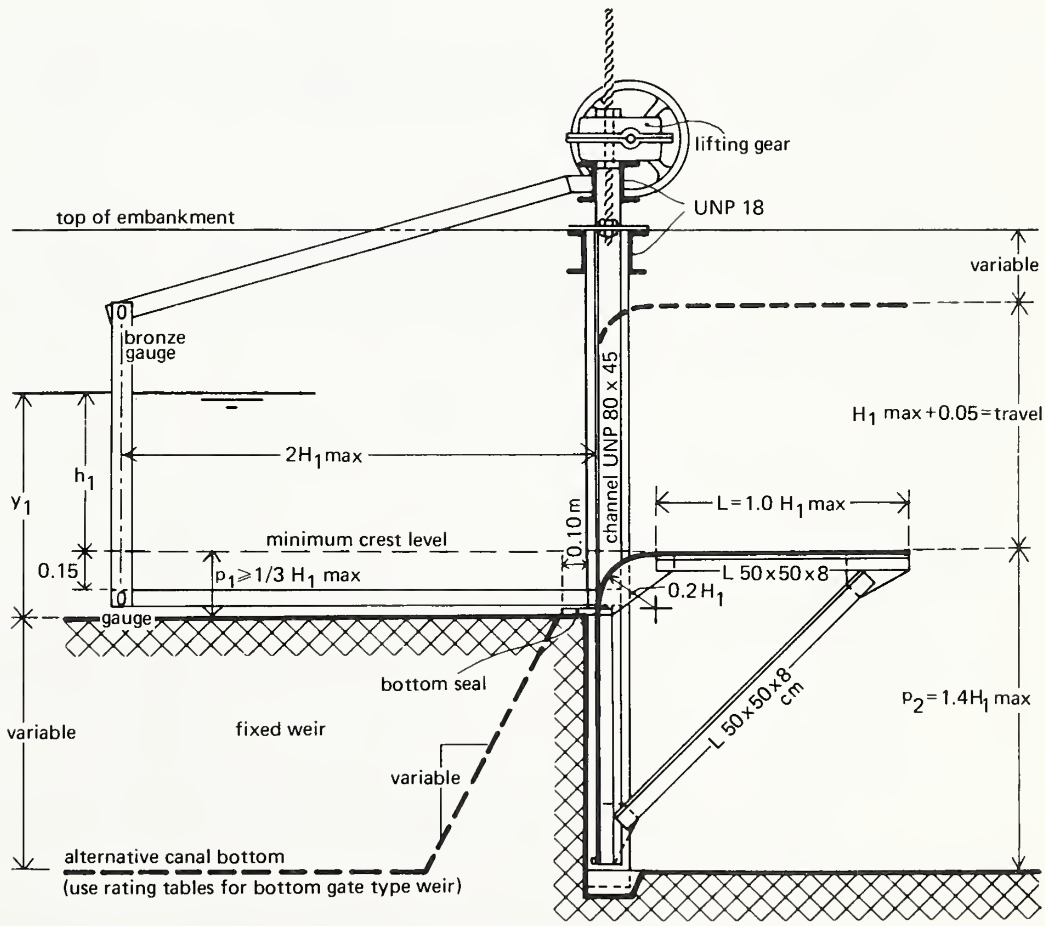

Figure 1.4.
Profile for broad-crested weir with vertically movable throat (bottom drop type).

2. HOW TO USE THE PROGRAM

2.1 Introduction

A computer program has been developed to solve the mathematical model for predicting discharge and required head loss for long-throated flumes, and a shortened version of it has been published (Bos et al. 1984). The program presented here provides the user with a variety of options that will enhance the usefulness and adaptability of these flumes to complex situations. The program--

1. Allows dimensions in either English or metric units.

2. Can be used to calibrate flumes differing widely in approach, throat and tailwater cross-sections, thus facilitating the use of these devices in a wide variety of channels.

3. Will provide calibrations either for a range of heads on a stationary flume or for a weir with a vertically movable crest and a fixed head.

4. Allows a selection of the flume dimensional head increment and output discharge units. (The flume dimensional and head increment units need not be the same).

5. Not only provides the traditional discharge for given head increments, but also interpolates and provides the head for given discharge increments, thus facilitating the construction of direct (discharge) reading wall gauges. (Logarithmic interpolation is used, since these head discharge relationships are nearly linear on logarithmic paper).

6. Has the option to read empirical head versus discharge data from a file for comparison with the discharge calculated by the computer model. (This comparison assumes that the empirically measured head is correct).

6. Writes data out to a disk file (if desired) for plotting or further use.

7. Makes available several options for rerunning the program without having to enter unchanged data. This includes changing the output device unit number so that output can be sent to a terminal, a printer or some other unit number. This is particularly useful since the program can be run several times with output to the terminal; then when a run is to be saved, it can be rerun and sent to the printer.

8. The program generates a head-discharge equation over the range of head values input. The regression coefficient is given along with an error analysis showing how well the equation fits the actual calibration.

The program given here is written in standard Fortran IV language for use on a Hewlett Packard 1000 series A, 16-bit mini-computer (RTE VI). The program performance on an 8-bit computer has not been tested. A number of the statements have been used which are unique to the computer system. In particular, these include statements which identify the compiler, allocate array storage, set up files, identify the program, control the printer, determine date and time of day and open and close files. These statements may require modification before the program can be used on other computer systems, and are clearly identified in the appendix. Also, the input, output, and file device numbers may need to be modified.

Many of the variables used in the computer program are not identical to those used in the text, since most computers do not use lower case letters or subscripts and have certain letters set aside as integers. However, the variables were chosen to match those in the text as closely as practical.

The program has been written so that it follows the computations given in chapter 3, step by step. The relative difference used to check convergence has been set to a small value, but due to the rapid convergence of the methods employed, computation time is not excessive.

The routines used in this model converge very rapidly for flumes which are properly configured. However, when there is not enough contraction in the channel to cause critical flow (which is required for a measurement), the solution will not converge. Thus, a counter is added to the program so that the computations will stop if the results are not converging (see Warnings 1 and 4 of section 2.3).

2.2 Program Inputs

The program is set up to read a series of input lines from a file or a terminal (depending on the user's computer system). Input variables are described in the computer printout that follows, and the sequence of input lines for an example, TEST RUN, is shown in table 2.1. The user need not know the theory in detail to provide the proper input. However, improper inputs may result in a number of warnings, which are given in section 2.3.

DETAILED DESCRIPTION OF INPUT VARIABLES (SEE TABLE 2.1):

LINE 1 - OUTPUT LOCATION

IO - OUTPUT UNIT NUMBER
= 1 : OUTPUT TO TERMINAL
= 6 : OUTPUT TO PRINTER

LINE 2 - RUN DESCRIPTION

THE IDENTIFICATION OF A PARTICULAR RUN IS ENTERED WITH UP TO 40 CHARACTERS.

LINE 3 - UNITS FOR FLUME DIMENSIONS

IOPT1 - INPUT UNIT OPTION
= 1 : FLUME DIMENSIONS IN METER
= 2 : FLUME DIMENSIONS IN FEET

LINE 4 - DEFINE CROSS SECTIONAL SHAPES

ISHP1 - SHAPE OPTION FOR APPROACH CHANNEL
ITROT - SHAPE OPTION FOR THROAT
ISHP2 - SHAPE OPTION FOR TAILWATER CHANNEL
SHAPE OPTIONS (SEE ADDITIONAL DETAIL WITH LINES 5,6,7)
= 1 : SIMPLE TRAPEZOID
= 2 : CIRCLE
= 3 : U-SHAPE
= 4 : PARABOLA
ADDITIONAL SHAPES FOR FLUME THROAT ONLY
= 5 : COMPLEX TRAPEZOID
= 6 : TRAPEZOID IN CIRCLE
= 7 : TRAPEZOID IN U-SHAPE
= 8 : TRAPEZOID IN PARABOLA

THE DATA REQUIRED IN LINES 5,6 AND 7 ARE DESCRIBED BELOW ACCORDING TO THE SHAPE OR SHAPES SPECIFIED IN LINE 4. THE X IS REPLACED BY 1,C OR 2 AS INDICATED.
THE UNITS FOR INPUT DIMENSIONS ARE SPECIFIED IN LINE 3.
(SEE FIGURE 2.1)

LINE 5 - APPROACH CHANNEL CROSS-SECTION DATA (X=1)
LINE 6 - THROAT CROSS-SECTION DATA (X=C)
LINE 7 - TAILWATER CHANNEL CROSS-SECTION DATA (X=2)

SHAPE OPTION 1 - SIMPLE TRAPEZOID
BX = BOTTOM WIDTH FOR SECTION X
ZX = SIDE SLOPE (HORIZONTAL TO VERTICAL) FOR SECTION X

SHAPE OPTION 2 - CIRCLE
DX = DIAMETER OF CIRCLE FOR SECTION X

SHAPE OPTION 3 - U-SHAPED
DX = DIAMETER OF CIRCLE FOR SECTION X

SHAPE OPTION 4 - PARABOLA
DX = FOCUS OF PARABOLA FOR SECTION X

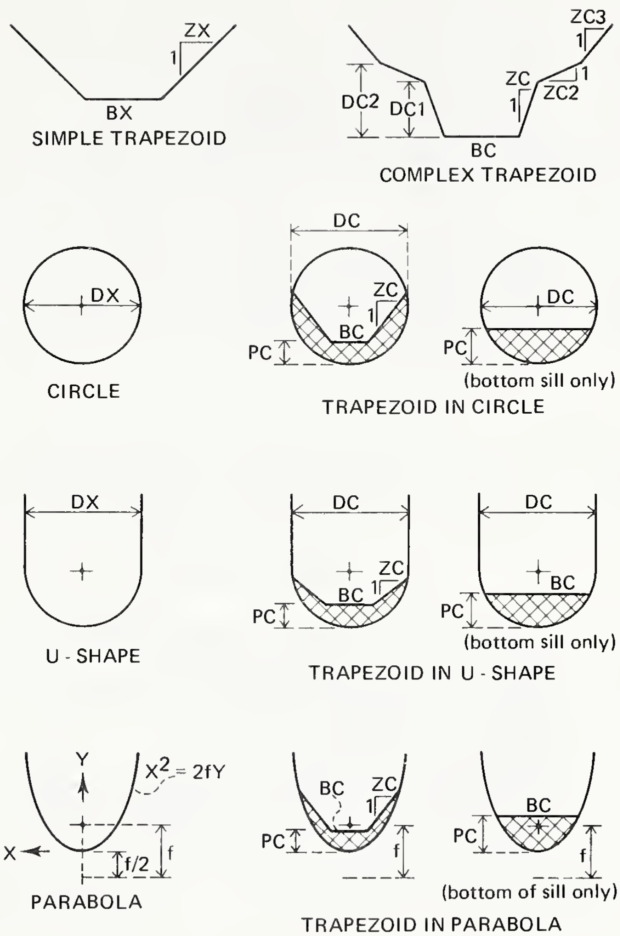

Figure 2.1.
Definition of terms for cross section shapes.

SHAPE OPTION 5 - COMPLEX TRAPEZOIDAL THROAT

BC	=	BOTTOM WIDTH FOR SECTION C
ZC	=	FIRST SIDE SLOPE (HORIZONTAL TO VERTICAL) FOR SECTION C
ZC2	=	SECOND SIDE SLOPE (HORIZONTAL TO VERTICAL) FOR SECTION C
ZC3	=	THIRD SIDE SLOPE (HORIZONTAL TO VERTICAL) FOR SECTION C
DC1	=	DEPTH AT JUNCTION BETWEEN FIRST AND SECOND SIDE SLOPE FOR SECTION C
DC2	=	DEPTH AT JUNCTION BETWEEN SECOND AND THIRD SIDE SLOPE FOR SECTION C

SHAPE OPTION 6 - TRAPEZOIDAL THROAT IN CIRCLE

DC	=	DIAMETER OF PIPE
PC	=	HEIGHT OF TRAPEZOID BOTTOM FROM CHANNEL INVERT
BC	=	BOTTOM WIDTH FOR TRAPEZOID (*)
ZC	=	SIDE SLOPE FOR TRAPEZOID

(*) FOR A BOTTOM SILL IN A CIRCLE, SPECIFY A BOTTOM WIDTH (BC) WIDER THAN THE SECTION WIDTH AT PC, AND A FLAT SIDE SLOPE.

SHAPE OPTION 7 - TRAPEZOIDAL THROAT IN U-SHAPE

DC = DIAMETER OF PIPE
PC = HEIGHT OF TRAPEZOID BOTTOM FROM CHANNEL INVERT
BC = BOTTOM WIDTH FOR TRAPEZOID (*)
ZC = SIDE SLOPE FOR TRAPEZOID
(*) FOR A BOTTOM SILL IN A U-SHAPE, SPECIFY A BOTTOM WIDTH (BC) WIDER THAN THE SECTION WIDTH AT PC, AND A FLAT SIDE SLOPE.

SHAPE OPTION 8 - TRAPEZOIDAL THROAT IN PARABOLA

DC = FOCUS OF PARABOLA
PC = HEIGHT OF TRAPEZOID BOTTOM FROM CHANNEL INVERT
BC = BOTTOM WIDTH FOR TRAPEZOID
ZC = SIDE SLOPE FOR TRAPEZOID

LINE 8 - SELECT THE WEIR TYPE

MOVE = 1 : FOR STATIONARY WEIR OR FLUME THROAT
MOVE = 2 : FOR WEIR WITH VERTICALLY MOVABLE CREST

LINE 9 - PROFILE DATA

LINE 9A - (1) FOR STATIONARY THROAT (SEE FIGURE 2.2)

AL = DISTANCE BETWEEN CONVERGING RAMP AND GAUGING STATION
BL = CONVERGING RAMP LENGTH
TL = THROAT LENGTH
P1 = SILL HEIGHT RELATIVE TO APPROACH CHANNEL
P2 = SILL HEIGHT RELATIVE TO TAILWATER CHANNEL
EM = DIVERGING TRANSITION RATIO (HORZ/VERT)
RK = ABSOLUTE ROUGHNESS HEIGHT OF MATERIAL
FOR CONCRETE FLUMES, A VALUE OF 0.0002 M IS OFTEN USEDFOR RK. ROUGHNESS VALUES FOR OTHER MATERIALS ARE GIVEN IN TABLE 3.2.

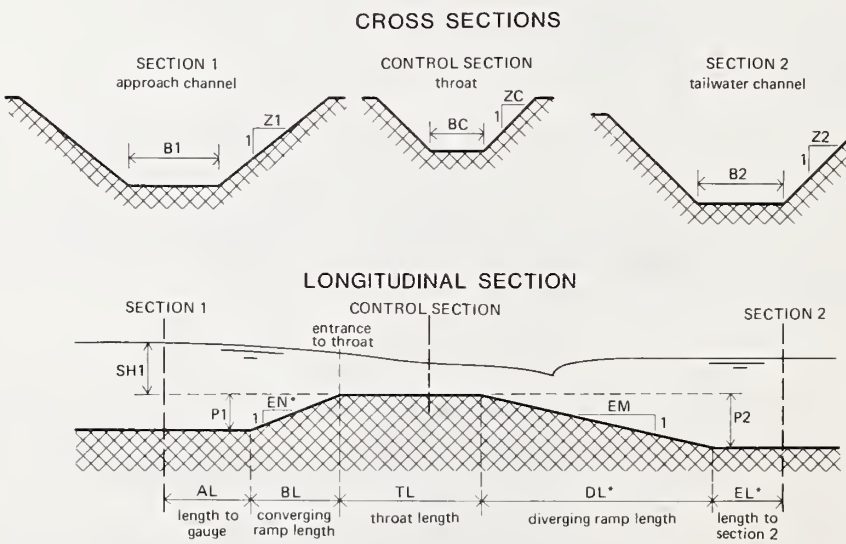

Figure 2.2.
Profile for flume or weir with stationary crest, showing computer input. (An * indicates that these data are not specified by the user. See figure 1.3 for recommended dimensions.

LINE 9B - (2) FOR MOVABLE WEIR CREST (SEE FIGURE 2.3)

AL = DISTANCE BETWEEN CONVERGING RAMP AND GAUGING STATION
RL = RADIUS OF CONVERGING TRANSITION
TL = THROAT LENGTH
Y1 = WATER DEPTH IN APPROACH CHANNEL (HELD CONSTANT)
DP = SILL HEIGHT DIFFERENCE BETWEEN APPROACH CHANNEL AND TAILWATER CHANNEL (P2-P1)
EM = DIVERGING TRANSITION RATIO (HORZ/VERT)- USUALLY ZERO
RK = ABSOLUTE ROUGHNESS HEIGHT OF MATERIAL
FOR CONCRETE FLUMES, A VALUE OF 0.0002 M IS OFTEN USED FOR RK. ROUGHNESS VALUES FOR OTHER MATERIALS ARE GIVEN IN TABLE 3.2.

LINE 10 - OUTPUT UNITS OPTION

JOPT1 - UNITS FOR DEPTH OUTPUT
= 1 : DEPTH IN METERS
= 2 : DEPTH IN MILLIMETERS
= 3 : DEPTH IN FEET
= 4 : DEPTH IN INCHES

JOPT2 - UNITS FOR DISCHARGE OUTPUT
= 1 : DISCHARGE IN CUBIC METERS PER SECOND
= 2 : DISCHARGE IN LITERS PER SECOND
= 3 : DISCHARGE IN CUBIC FEET PER SECOND
= 4 : DISCHARGE IN GALLONS PER MINUTE
= 5 : DISCHARGE IN ACRE-FEET PER HOUR
= 6 : MINER'S INCHES (=1/40 FT3/S)
= 7 : CUBIC DEKAMETERS (MEGALITERS)/HR
= 8 : MILLION GALLONS PER DAY (MGD)

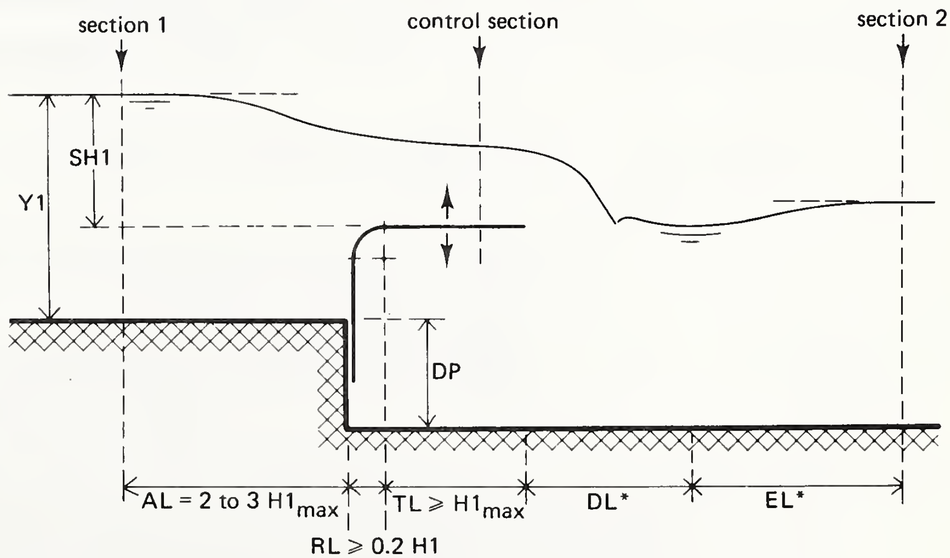

Figure 2.3.
Profile for weir with vertically movable crest, showing computer input. (An * indicates that these data are not specified by the user). See figures 1.3 and 1.4 for recommended dimensions.

LINE 11 - DEPTH AND DISCHARGE INCREMENT

(UNITS SPECIFIED IN LINE 10)

HLOW = LOWEST HEAD FOR CALIBRATION
HINC = INCREMENT IN HEAD VALUES
HHIGH = HIGHEST HEAD FOR CALIBRATION
QINC = INCREMENT IN DISCHARGE VALUES FOR INVERSE RATING (SET TO ZERO TO SKIP THIS OPTION)

LINE 12 - SAVE DATA FOR PLOT OPTION

F1 - STORE DATA FROM ORIGINAL RATING TABLE
F2 - STORE DATA FOR WALL GAUGE PLOT
YES = 1 : CREATE FILE AND STORE DATA
NO = 0 : NO FILE CREATED

LINE 12A - INPUT FILE NAME FOR RATING TABLE DATA (F1=1)
LINE 12B - INPUT FILE NAME FOR WALL GAUGE DATA (F2=1)
(FILE NAMES ARE LIMITED TO 6 CHARACTERS)

LINE 13 - ANALYZE FIELD DATA OPTION

YES = 1 : READ FIELD DATA FOR COMPARISON
NO = 0 : NO FIELD DATA COMPARISON
LINE 13A - INPUT FILE NAME FOR FIELD DATA
LINE 13B - INPUT UNITS FOR FIELD DATA (SEE LINE 10)
LINE 13C - STORE DATA FOR FIELD DATA COMPARISON
YES = 1 : CREATE FILE AND STORE DATA
NO = 0 : NO FILE CREATED
LINE 13C1 - INPUT FILE NAME FOR FIELD DATA COMPARISON

LINE 14 - CONTINUATION OPTION

= 0 : STOP
= 1 : READ ALL NEW INPUT DATA, STARTING WITH LINE 1
= 2 : READ NEW PROFILE DIMENSIONS, ETC
READS LINE 2, THEN SKIPS TO LINE 8
= 3 : READ NEW OUTPUT UNITS, ETC
READS LINE 2, THEN SKIPS TO LINE 10
= 4 : READS NEW OUTPUT UNIT NUMBER, THEN SKIPS REMAINING INPUT

THE USER SHOULD NOTE THAT THE LENGTH OF THE DIVERGING TRANSITION (DL) IS BASED ON THE PRODUCT OF P2*EM. THUS WHEN P2=0, THEN DL=0, SO THAT WHEN ONLY A SIDE CONTRACTION IS USED, THE DIVERGING TRANSITION LENGTH IS ZERO. THE LENGTH DL IS ONLY USED IN FRICTION CALCULATIONS. THE RESULTING ENERGY LOSS IS SMALL COMPARED TO THE EXPANSION LOSS RESULTING FROM EM. THUS IT IS MORE IMPORTANT TO CORRECTLY SPECIFY EM AND ACCEPT AN ERROR IN DL. PROPER ACCOUNTING FOR DL FOR THESE CASES IS NOT WORTH THE ADDED COMPLEXITY FOR THE GENERAL CASE. USE THE LARGER VALUE OF THE EXPANSION RATIO FROM THE BOTTOM OR FROM THE SIDES.

Table 2.1
Sequence of input data

Line No.	Function	Example	Explanation
1	Select unit number for output device	6	Output to printer
2	Run Description	TEST RUN	
3	Select units for flume dimensions	1	Metric units (meters)
4	Select cross-section shapes	1,6,4	Trapezoidal approach; throat trapezoid in a circle, parabolic tailwater channel
5	Define approach cross-section	0.5,1	B1, Z1
6	Define throat cross-section	.75, 0.2, 0.2, 1	DC, PC, BC, ZC
7	Define tailwater cross-section	3	D2
8	Select stationary or movable weir	1	Stationary weir
9	Define profile and roughness	0.3, 0.9, 0.6, 0.3, 0.4, 0, 0.0002	AL, BL, TL, P1, P2, EM, RK
10	Select units for output	2,2	Output in mm and 1/s
11	Define range and increments for head and discharge	100, 20, 400, 20	HLOW, HINK, HHIGH, QINC
12	Select output options for plotting	0,0	Computations not stored (no files created)
13	Select option for field data comparison	0	No field data
14	Select options for next run	0	Stop

2.3 Program Warnings

A series of checks in the program ensure that the input data are not in error. In general, the program checks to be sure that a structure with the given shape will act like a flume in the given channel and that an accurate rating can be derived. Conditions that cause warnings are given in table 2.2. Termination occurs only when the contraction in flow area from the approach channel to the flume throat is not sufficient to cause critical flow or when the limits on the sill-referenced head are unrealistic. (See Warnings 1, 8, and 9.) The other warnings or cautions basically indicate that the flume dimensions have not been chosen according to the recommended specifications. These recommendations are shown in figures 1.3 and 1.4. The program will execute anyway; however, the rating table may not produce accurate estimates of the true discharge and/or required head loss.

Most of these warnings are printed prior to execution of the run. The Froude number warning is not printed until the run is made, since the discharge is not known prior to the run. Some examples are given in section 2.5.

2.4. Program Outputs

The primary program output for example TEST RUN is shown in table 2.3. In accordance with table 2.1, the run description is printed first (line 2). Next, the cross section data are given for each flume section, with dimensions given in the specified units (meters in this case) (line 3). Note that different cross sectional shapes are used for the three sections (line 4). This is probably an unrealistic combination but does reflect the versatility of the program. The actual parameters defining each cross section are given (lines 5, 6, and 7). The type of flume (line 8) and the profile data are given next (line 9). The lengths of the diverging transition and tailwater channel are computed and printed here to show what lengths were used in the calculation of head loss. Also computed is the slope (horizontal to vertical) of the converging transition, assuming a bottom contraction only. These input data, which define the flume, are followed by warnings to the user about potential problems having to do with either the calculations which determine the printed output or the limitations placed on the flume dimensions and suitability (see section 2.3).

Table 2.2
Conditions that cause warnings and/or program termination[1]

IWARN	Conditions	Results
1	Not enough contraction in flow area from approach channel to throat.	Terminates run if flow area actually expands. Otherwise, prints warning and may terminate if rating not obtainable.
2	Converging transition ramp flatter than 3:1.	Prints warning--ramp may be flatter than desired, but rating should still be reasonably accurate. Ignore when side contraction or movable throat is used.
3	Converging transition ramp steeper than 2:1, or radius of converging transition may be too small.	Prints warning--flume rating may not be reliable. Ignore when rounded converging section used.
4	Not enough expansion in flow area from throat to tailwater channel.	Prints warning--modular limit and head loss calculations may not be accurate.
5	Tailwater channel bottom above approach channel bottom.	Prints warning--modular limit and head loss calculations may not be accurate.
6	Diverging transition ramp too flat.	Prints warning--ramp slope is set at 10:1.
7	Absolute roughness height less than 0.000001 m or greater than 0.01 m.	Prints warning--sets RK to 0.0002 m if RK > 0.01 m.
8	Error in head limit range (for example, HLOW < 0.0, HLOW > HHIGH, or more than 200 head increments).	Program prints values for HLOW, HINC, HHIGH, and then terminates run. For movable weirs, HHIGH is limited to y_1.
9	Limits on H_1/L exceeded-- $h_1/L < 0.07$ or $h_1/L > 0.7$.	Prints warning--indicating which limit is exceeded. Run terminated when $h_1/L < 0.04$.
10	Gauging station may be too close to flume throat.	Prints warning--gauging station should be moved to proper location; otherwise the rating may not be accurate.
11	Froude number exceeds 0.5.	Prints warning at each head that Froude number is exceeded. When the Froude number exceeds 0.7, the run is terminated.

[1] See figures 1.3 and 1.4 for recommended flume dimensions. Example error messages given in tables 2.3, 2.6, and 2.8.

The computed rating table is printed next. The units for this table are determined by the values given in line 10. The computations begin with the lowest sill-referenced head or upstream water level, follow with each successive head according to the increment given, and end with the highest head (line 11). The program is set up to determine head values as multiples of the head increment. If the lowest sill-referenced head is not a multiple of the head increment, the next lowest head increment is chosen as the lowest head value--unless it is zero, in which case the first increment is chosen. The program is currently limited to 200 head increments. At each head, a number of parameters are computed and printed. The column headings are explained in table 2.4. The output also indicates whether these data have been stored in a data file and, if they have, the name of the file (see lines 12 and 12A). Further explanations are given in section 2.5 and the appendix.

The next set of data comprise an inverse rating table; that is, this table gives computed head values, h_1, for discharge values which are multiples of QINC (line 11). When QINC = 0, the program will not print this table. For simple trapezoidal approach channels, the distance along the side slope for each discharge value is given to facilitate the construction of a wall gauge which reads directly in discharge units. For channels of other shapes, a direct reading gauge can be mounted on a vertical support, and only the vertical head is output. These data can be output to a file for later plotting of a wall gauge template in discharge units rather than the traditional head units (lines 12 and 12B). An example is given in section 2.5.

Next the program automatically computes a head discharge equation of the form $Q = A\,(h_1 + B)^u$. The units on B are the same as h_1, u is unitless, and the units for A vary with the units for Q and h_1 and the value of u. In the output, the units for Q and h_1 are given, while only values are shown for A, B and u. The regression coefficient of determination, r^2, is printed next. This coefficient of determination is based on the sum of squares of the errors in logarithmic values (LN). Finally, the original data h_1 and Q as well as the predicted discharge, Q(CALC), and the associated errors, both absolute and in percent, are printed. Note that a much better fit to the data can be obtained if a narrower range of heads is specified on input.

The printout may contain an additional optional table (see example, section 2.5), depending upon whether field or laboratory data are available for a comparison (line 13). If they

are available, the field data on discharge are read from a data file (line 13A) and compared with the model data for each head value. The units on the field data need not be the same as those for the rating table (line 13B). These data can be written to a data file for further analysis or plotting (line 13C). See the appendix for an explanation on file handling.

Table 2.3
Output for example TEST RUN

```
TEST RUN                                TIME = 10:40     DATE =113:1986

CROSS SECTION DATA

   APPROACH CHANNEL
   SIMPLE TRAPEZOID
     BOTTOM WIDTH            B1 =    .500     M
     SIDE SLOPE              Z1 =   1.000   : 1

   THROAT SECTION
   TRAPEZOID IN CIRCLE
     DIAMETER                DC =    .750     M
     SILL HEIGHT             PC =    .200     M
     BOTTOM WIDTH            BC =    .200     M
     SIDE SLOPE              ZC =   1.000   : 1

   TAILWATER CHANNEL
   PARABOLA
     FOCUS                   D2 =   3.000     M


PROFILE DATA

   STATIONARY WEIR
   ---------------
   LENGTH TO GAUGE         AL =    .300     M
   CON RAMP LENGTH         BL =    .900     M
   THROAT LENGTH           TL =    .600     M
   DIV RAMP LENGTH        *DL =   0.000     M
   LENGTH TO SEC 2        *EL =   7.000     M
   CON SILL HEIGHT         P1 =    .300     M
   CON RAMP SLOPE         *EN =   3.000   : 1
   DIV SILL HEIGHT         P2 =    .400     M
   DIV RAMP SLOPE          EM =   0.000   : 1

   MATERIAL ROUGHNESS      RK =.0002000     M

     WARNING IWARN = 10
          GAUGE MAY BE TOO CLOSE TO RAMP
```

Table 2.3--Continued
Output for example TEST RUN

RATING TABLE TEST RUN

SILL REFER. HEAD SH1 MM	FLOW RATE Q LIT/SEC	FROUDE NO. FR1	H1/TL	DISH. COEFF. CD	VELOC. COEFF. CV	REQ'D HEAD LOSS DH MM	MAX. T-WATER DEPTH Y2 MM	MODULAR LIMIT
100.0	14.106	.024	.167	.9706	1.001	33.0	467.1	.670
120.0	19.593	.030	.200	.9734	1.002	38.5	481.6	.680
140.0	26.016	.037	.234	.9756	1.003	43.7	496.4	.688
160.0	33.412	.043	.267	.9775	1.004	48.7	511.5	.696
180.0	41.817	.050	.301	.9791	1.004	53.6	526.7	.703
200.0	51.269	.057	.334	.9804	1.005	58.2	542.2	.710
220.0	61.804	.063	.368	.9816	1.006	62.7	557.8	.716
240.0	73.462	.070	.402	.9827	1.007	67.1	573.6	.721
260.0	86.277	.077	.435	.9835	1.009	71.4	589.5	.727
280.0	100.288	.083	.469	.9843	1.010	75.5	605.6	.732
300.0	115.531	.090	.503	.9851	1.011	79.5	621.8	.736
320.0	132.039	.096	.537	.9859	1.012	83.4	638.1	.741
340.0	149.843	.102	.570	.9865	1.014	87.3	654.5	.745
360.0	168.795	.109	.604	.9870	1.015	93.0	669.0	.743
380.0	188.384	.114	.638	.9875	1.015	100.1	682.2	.739
400.0	208.528	.119	.672	.9879	1.016	107.3	695.3	.734

WALL GAUGE DATA TEST RUN

FLOW RATE Q LIT/SEC	SILL REFER. HEAD SH1 MM	WALL GAUGE DIST. SHS MM
20.0	121.3	171.6
40.0	175.9	248.7
60.0	216.7	306.5
80.0	250.4	354.1
100.0	279.6	395.4
120.0	305.6	432.1
140.0	329.1	465.4
160.0	350.9	496.2
180.0	371.6	525.5
200.0	391.7	553.9

Table 2.3--Continued
Output for example TEST RUN

DISCHARGE EQUATION   TEST RUN

EQUATION Q = A * (SH1 +B)**U

Q IN LIT/SEC   SH1 IN MM

COEFFICIENT VALUES

A = .5643E-03
B = 16.80
U = 2.1242

GOODNESS OF FIT

COEFFICIENT OF DETERMINATION (LN) R2 = 1.000

DATA

SH1 MM	Q LIT/SEC	Q(CALC) LIT/SEC	ERROR LIT/SEC	%ERROR
100.0	14.106	13.903	-.203	-1.440
120.0	19.593	19.450	-.143	-.730
140.0	26.016	25.990	-.026	-.102
160.0	33.412	33.539	.127	.381
180.0	41.817	42.113	.296	.708
200.0	51.269	51.725	.456	.889
220.0	61.804	62.389	.585	.946
240.0	73.462	74.115	.653	.889
260.0	86.277	86.914	.637	.738
280.0	100.288	100.797	.509	.508
300.0	115.531	115.773	.242	.210
320.0	132.039	131.851	-.188	-.142
340.0	149.843	149.039	-.804	-.537
360.0	168.795	167.345	-1.451	-.859
380.0	188.384	186.777	-1.607	-.853
400.0	208.528	207.341	-1.187	-.569

Table 2.4
Explanation of program output for computed rating table

Column	Value	Description
1	SH1 = h_1	The sill-referenced head. This is the head measured at the gauging station for determining discharge.
2	Q	The predicted flow rate for the given h_1.
3	FR1 = F_{r1}	The Froude number of the flow in the approach channel. This value should be less than 0.5 in all cases and less than 0.45 when the approach conditions are not totally smooth.
4	H1/TL = H_1/L	The ratio of energy head to throat length. The head, h_1, over which rating can be reliably computed is limited to $0.075 < H_1/L < 0.75$. See section 3.3.3.
5	CD = C_d	Discharge coefficient, the ratio between actual and ideal flow.
6	CV = C_v	The velocity coefficient which is computed for reference purposes only. It is the ratio between flow based on energy head, H_1, and water depth h_1.
7	DH = ΔH	This is the required energy loss across the flume, H_2-H_1. This may differ from the required difference in water levels, $\Delta h = h_2 - h_1$.
8	Y2 = y_2	This is the maximum flow depth in the tailwater channel for which there is no influence of this depth on the Q-h_1 relationship, $y_2 = h_2 + p_2$.
9	ML	This is the modular limit defined in terms of the ratio of downstream to upstream energy heads, H_2/H_1, at the limit between modular and nonmodular flow. Modular flow exists when the Q-h_1 relationship is not affected by the flow in the tailwater channel.

2.5 Options

This program is versatile in its application to flow measurement problems. Table 2.3 shows some of the versatility in relation to flume cross section shapes. This, along with the dimensional unit's option and the movable weir option, provides for a wide range of calibrations. The program also has a number of options that assist in data analysis and manipulation. These options are best demonstrated with an example.

Table 2.5 gives both the input data for an example with laboratory flume no. 7 from Replogle (1978) and an explanation of what each data line represents. Further explanations can be found in the printout of section 2.2. This example utilizes some of the file handling options. The output is given in table 2.6. The rating table information is output to file J7R, as indicated at the bottom of this table. Figure 2.4 shows a plot of h_1 versus Q and h_2 versus Q, as plotted from file J7R. The wall gauge data were output to file J7G and plotted as shown in figure 2.5. Such a plot can be used for constructing a wall gauge. Field data were read from file JRD7, and a comparison is given in the last table within table 2.6. These comparison data were stored in file J7F. A plot of C_d versus H_1/L for the computed and measured data (from file J7F) is shown in figure 2.6. The data files (J7R, J7G, JRD7, J7F) are given in the appendix, (tables A1, A2, A3 and A4 respectively).

A final example illustrates additional program options. This example is for a movable weir in English units. The input is given in table 2.7, and the output is shown in table 2.8. Note that Warning 1 appears in table 2.8, indicating an obvious error and that the values following the warning show $y_1 = y_c = 1.0$ ft. Note from the input that $y_1 = 1.0$ and $h_{1max} = 1.0$; thus $p_1 = y_1 - h_{1max} = 0$. With $b_1 = b_c$, there is no constriction in flow. The rating table output confirms this; the Froude number became so high that the run was terminated prior to reaching HHIGH. For movable weirs, a negative sill is not allowed and HHIGH is limited to Y1. Note also the poor fit to the flume calibration equation caused by the large shift in approach section Froude number.

The continuation option was used to run a new calibration for the same flume with different output units. However, the output limits on head were not changed to reflect this, and the calibration was out of the useful H/L range.

Table 2.5
Input data for example with FLUME #7

Line	Data	Explanation
1	6	Output to printer
2	FLUME #7	Run description
3	1	Metric units
4	1, 1, 1	All shapes simple trapezoids
5	.203, .577	Cross-section data
6	.002, .581	Cross-section data
7	.203, .577	Cross-section data
8	1	Stationary crest
9	.152, .914, .914, 0, 0, 0, 0.0000015	Profile data
10	2, 2	Output in mm and l/s
11	50, 10, 440, 10	Ranges of head and discharge
12	1, 1	Output files to be created and opened
12A	J7R	Output file for rating table data
12B	J7G	Output file for gauge plot data
13	1	Field (lab) data are to be analyzed
13A	JRD7	Input file for field data
13B	2, 2	Units are mm and l/s.
13C	1	Output file to be created and opened
13C1	J7F	Output file for field data comparison
14	0	Stop

Table 2.6
Output for example FLUME #7

```
FLUME #7                                         TIME = 10:40     DATE =113:1986


CROSS SECTION DATA

   APPROACH CHANNEL

   SIMPLE TRAPEZOID
     BOTTOM WIDTH          B1 =    .203    M
     SIDE SLOPE            Z1 =    .577  : 1

   THROAT SECTION
   SIMPLE TRAPEZOID
     BOTTOM WIDTH          BC =    .002    M
     SIDE SLOPE            ZC =    .581  : 1

   TAILWATER CHANNEL
   SIMPLE TRAPEZOID
     BOTTOM WIDTH          B2 =    .203    M
     SIDE SLOPE            Z2 =    .577  : 1

PROFILE DATA

   STATIONARY WEIR
   ---------------
   LENGTH TO GAUGE        AL =    .152    M
   CON RAMP LENGTH        BL =    .914    M
   THROAT LENGTH          TL =    .914    M
   DIV RAMP LENGTH       *DL =   0.000    M
   LENGTH TO SEC 2       *EL =   4.570    M
   CON SILL HEIGHT        P1 =   0.000    M
   CON RAMP SLOPE        *EN =  99.999  : 1
   DIV SILL HEIGHT        P2 =   0.000    M
   DIV RAMP SLOPE         EM =   0.000  : 1

   MATERIAL ROUGHNESS     RK =.0000015    M


     CAUTION IWARN = 9
          H/L RATIO IS LESS THAN 0.07

     WARNING IWARN = 10
          GAUGE MAY BE TOO CLOSE TO RAMP
```

Table 2.6--Continued
Output for example FLUME #7

RATING TABLE FLUME #7

SILL REFER. HEAD SH1 MM	FLOW RATE Q LIT/SEC	FROUDE NO. FR1	H1/TL	DISH. COEFF. CD	VELOC. COEFF. CV	REQ'D HEAD LOSS DH MM	MAX. T-WATER DEPTH Y2 MM	MODULAR LIMIT
50.0	.385	.050	.055	.8567	1.003	11.1	38.9	.779
60.0	.612	.060	.066	.8751	1.004	12.4	47.5	.793
70.0	.906	.069	.077	.8881	1.005	13.7	56.2	.805
80.0	1.271	.078	.088	.8978	1.007	14.9	65.0	.814
90.0	1.714	.087	.099	.9049	1.008	16.0	73.8	.823
100.0	2.238	.096	.110	.9108	1.010	17.0	82.7	.830
110.0	2.852	.104	.121	.9165	1.011	18.1	91.7	.837
120.0	3.566	.113	.132	.9233	1.013	19.1	100.5	.842
130.0	4.380	.121	.143	.9292	1.015	20.1	109.5	.846
140.0	5.298	.129	.154	.9343	1.017	21.0	118.5	.851
150.0	6.324	.137	.165	.9387	1.019	21.9	127.5	.855
160.0	7.464	.144	.177	.9426	1.021	22.8	136.6	.859
170.0	8.720	.152	.188	.9461	1.023	23.6	145.7	.863
180.0	10.098	.159	.199	.9492	1.025	24.3	154.8	.866
190.0	11.602	.166	.210	.9520	1.027	25.1	164.0	.869
200.0	13.235	.173	.221	.9545	1.029	25.8	173.2	.873
210.0	15.002	.180	.233	.9568	1.031	26.4	182.5	.876
220.0	16.906	.187	.244	.9589	1.033	27.1	191.7	.879
230.0	18.952	.193	.255	.9608	1.035	27.7	201.0	.881
240.0	21.143	.199	.266	.9625	1.037	28.3	210.3	.884
250.0	23.483	.206	.278	.9644	1.039	28.8	219.6	.886
260.0	25.977	.212	.289	.9659	1.041	29.4	229.0	.889
270.0	28.626	.217	.300	.9673	1.043	29.9	238.3	.891
280.0	31.436	.223	.312	.9685	1.045	30.4	247.7	.893
290.0	34.410	.229	.323	.9697	1.047	30.9	257.1	.896
300.0	37.551	.234	.335	.9709	1.049	31.3	266.5	.898
310.0	40.863	.240	.346	.9720	1.051	31.8	276.0	.900
320.0	44.349	.245	.358	.9730	1.054	32.2	285.4	.901
330.0	48.013	.250	.369	.9739	1.056	32.6	294.9	.903
340.0	51.858	.256	.380	.9748	1.058	33.0	304.4	.905
350.0	55.888	.261	.392	.9757	1.060	33.4	313.8	.907
360.0	60.105	.265	.403	.9765	1.062	33.9	323.6	.908
370.0	64.574	.271	.415	.9781	1.064	34.3	332.8	.910
380.0	69.164	.275	.427	.9786	1.066	34.6	342.2	.911
390.0	73.951	.280	.438	.9791	1.068	35.0	351.5	.913

Table 2.6--Continued
Output for example FLUME #7

RATING TABLE--Con.   FLUME #7

SILL REFER. HEAD SHI MM	FLOW RATE Q LIT/SEC	PROUDE NO. FRI	H1/TL	DISH. COEFF. CD	VELOC. COEFF. CV	REQ'D HEAD LOSS DH MM	MAX. T-WATER DEPTH Y2 MM	MODULAR LIMIT
400.0	78.938	.284	.450	.9795	1.070	35.3	360.9	.914
410.0	84.129	.289	.461	.9800	1.072	35.7	370.7	.915
420.0	89.527	.293	.473	.9802	1.074	36.1	380.2	.916
430.0	95.134	.297	.484	.9806	1.075	36.4	389.8	.918
440.0	100.955	.302	.496	.9811	1.077	36.7	399.3	.919

(J7R) WAS CREATED FOR RATING TABLE DATA

WALL GAUGE DATA   FLUME #7

FLOW RATE Q LIT/SEC	SILL REFER. HEAD SH1 MM	WALL GAUGE DIST. SHS MM
10.0	179.3	207.0
20.0	234.9	271.2
30.0	275.0	317.5
40.0	307.4	355.0
50.0	335.2	387.0
60.0	359.8	415.3
70.0	381.8	440.8
80.0	402.1	464.2
90.0	420.9	485.9
100.0	438.4	506.1

(J7G) WAS CREATED FOR GAUGE PLOT DATA

DISCHARGE EQUATION   FLUME #7

EQUATION Q = A * (SH1 +B)**U

Q IN LIT/SEC   SH1 IN MM

COEFFICIENT VALUES
A = .1518E-04
B = .8800
U = 2.5798

Table 2.6.--Continued
Output for example FLUME #7

GOODNESS OF FIT
COEFFICIENT OF DETERMINATION (LN) R2 = 1.000

DATA

SH1 MM	Q LIT/SEC	Q(CALC) LIT/SEC	ERROR LIT/SEC	%ERROR
50.0	.385	.383	-.001	-.289
60.0	.612	.609	-.003	-.485
70.0	.906	.902	-.004	-.436
80.0	1.271	1.268	-.004	-.278
90.0	1.714	1.713	-.001	-.054
100.0	2.238	2.242	.004	.188
110.0	2.852	2.861	.009	.330
120.0	3.566	3.575	.009	.244
130.0	4.380	4.388	.008	.190
140.0	5.298	5.306	.008	.158
150.0	6.324	6.333	.009	.141
160.0	7.464	7.474	.010	.133
170.0	8.720	8.732	.011	.130
180.0	10.098	10.111	.013	.130
190.0	11.602	11.617	.015	.133
200.0	13.235	13.253	.018	.138
210.0	15.002	15.023	.021	.141
220.0	16.906	16.930	.024	.141
230.0	18.952	18.978	.027	.141
240.0	21.143	21.172	.029	.138
250.0	23.483	23.515	.031	.133
260.0	25.977	26.009	.033	.127
270.0	28.626	28.660	.034	.119
280.0	31.436	31.470	.034	.107
290.0	34.410	34.442	.032	.094
300.0	37.551	37.580	.029	.078
310.0	40.863	40.887	.025	.061
320.0	44.349	44.367	.018	.042
330.0	48.013	48.022	.010	.020
340.0	51.858	51.857	-.002	-.003
350.0	55.888	55.872	-.016	-.028
360.0	60.105	60.073	-.031	-.052
370.0	64.574	64.463	-.112	-.173
380.0	69.164	69.042	-.122	-.176
390.0	73.951	73.816	-.135	-.182
400.0	78.938	78.787	-.151	-.192
410.0	84.129	83.958	-.171	-.204
420.0	89.527	89.331	-.196	-.218
430.0	95.134	94.910	-.224	-.236
440.0	100.955	100.697	-.258	-.256

Table 2.6--Continued
Output for example FLUME #7

FIELD DATA COMPARISON FLUME #7
DATA FROM JRD7

SH1 MM	MEASURED Q LIT/SEC	MODEL Q LIT/SEC	IDEAL Q LIT/SEC	MODEL H1/L	MEASURED CD	MODEL CD	PERCENT DIFFERENCE
56.4	.532	.523	.602	.0618	.8843	.8692	-1.73
57.9	.569	.559	.641	.0634	.8872	.8718	-1.77
85.0	1.495	1.482	1.645	.0933	.9091	.9015	-.85
151.5	6.560	6.488	6.907	.1670	.9498	.9394	-1.11
170.1	8.720	8.733	9.230	.1878	.9447	.9461	.15
189.0	11.310	11.446	12.026	.2090	.9404	.9517	1.19
189.9	11.580	11.586	12.171	.2100	.9515	.9520	.05
200.0	13.470	13.235	13.866	.2213	.9715	.9545	-1.78
221.0	17.240	17.104	17.834	.2450	.9667	.9591	-.79
257.0	25.200	25.212	26.115	.2857	.9650	.9654	.05
265.0	26.900	27.281	28.225	.2948	.9531	.9666	1.40
328.0	47.200	47.265	48.541	.3667	.9724	.9737	.14
329.0	47.400	47.638	48.919	.3678	.9689	.9738	.50
338.0	50.800	51.074	52.404	.3782	.9694	.9746	.54
355.0	57.700	57.974	59.395	.3977	.9715	.9761	.47
377.0	67.000	67.767	69.257	.4231	.9674	.9785	1.13
399.0	77.700	78.430	80.072	.4485	.9704	.9795	.93
409.0	82.700	83.601	85.312	.4601	.9694	.9799	1.08
411.0	84.200	84.659	86.385	.4624	.9747	.9800	.54
440.0	100.100	100.955	102.903	.4960	.9728	.9811	.85

(J7F) WAS CREATED FOR FIELD DATA COMPARISON

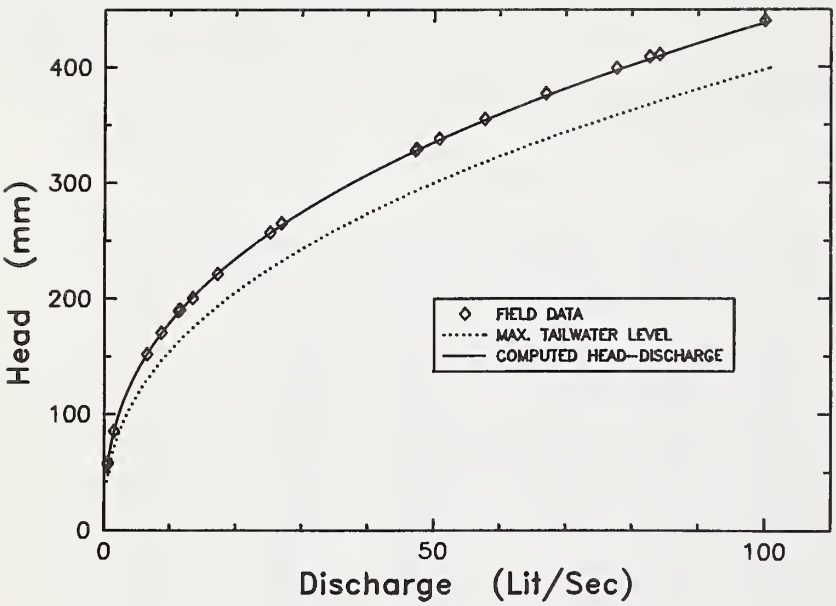

Figure 2.4.
Relation between discharge and head for both the flume rating and maximum tailwater level for FLUME #7, as plotted from files J7R and J7F.

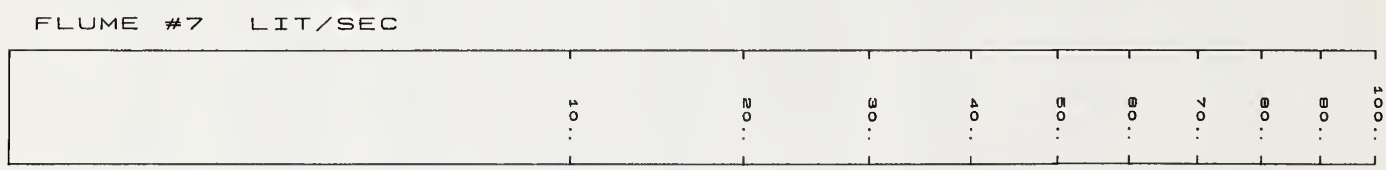

Figure 2.5.
Wall gauge template for FLUME #7, as plotted from file J7G.

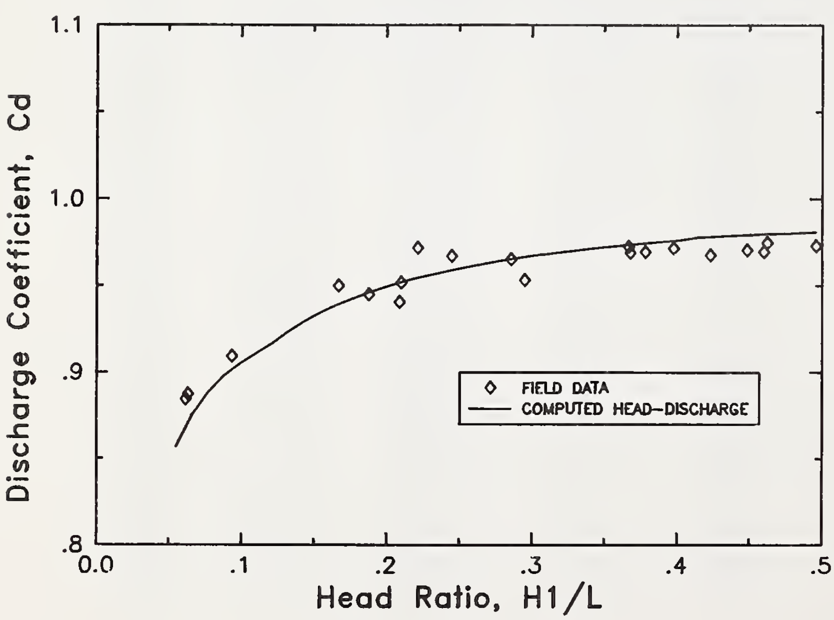

Figure 2.6.
C_d versus H_1/L for FLUME #7, as plotted from files J7R and J7F.

Table 2.7
Input data for example MOVABLE WEIR

Line	Data	Explanation
1	6	Output to printer
2	MOVABLE WEIR	Title
3	2	English units
4	1, 1, 1	Simple trapezoids
5	2, 0	Cross-section data (rectangular)
6	2, 0	Cross-section data (rectangular)
7	2, 0	Cross-section data (rectangular)
8	2	Movable weir selected
9	1, .33, 1.5, 1.0, 1, 0, .0005	Profile data
10	3, 3	Output in ft and ft^3/s
11	.1, .05, 1, 1	Head data
12	0, 0	No output files
13	0	No field data
14	3	Rerun with different output
2	MW #2	Title
10	4, 5	Output in inch and Acre-ft
11	.1, .05, .5, .5	Head data
12	0, 0	No output files
13	0	No field data
14	0	Stop

Table 2.8
Output data for example MOVABLE WEIR

```
MOVABLE WEIR                                TIME = 10:40     DATE =113:1986

CROSS SECTION DATA

   APPROACH CHANNEL
   SIMPLE TRAPEZOID
     BOTTOM WIDTH          B1 =  2.000   FT
     SIDE SLOPE            Z1 =  0.000  : 1

   THROAT SECTION
   SIMPLE TRAPEZOID
     BOTTOM WIDTH          BC =  2.000   FT
     SIDE SLOPE            ZC =  0.000  : 1

   TAILWATER CHANNEL
   SIMPLE TRAPEZOID
     BOTTOM WIDTH          B2 =  2.000   FT
     SIDE SLOPE            Z2 =  0.000  : 1

PROFILE DATA

   MOVABLE WEIR
   ------------
   LENGTH TO GAUGE       AL =  1.000   FT
   CON TRAN RADIUS       RL =   .330   FT
   THROAT LENGTH         TL =  1.500   FT
   DIV RAMP LENGTH      *DL =  0.000   FT
   LENGTH TO SEC 2      *EL = 20.000   FT
   MAXIMUM DEPTH         Y1 =  1.000   FT
   BOTTOM DROP           DP =  1.000   FT
   DIV RAMP SLOPE        EM =  0.000  : 1

   MATERIAL ROUGHNESS    RK =.0005000  FT

     WARNING IWARN = 1
          CAUTION - HIGH FROUDE NUMBERS MAY RESULT
          OR PROGRAM MAY NOT CONVERGE
          CHECK FOLLOWING DATA

Y1,B1,Z1,D1,A1,TW1 ARE
  1.000  2.000  0.000  0.000  2.000  2.000
YC,BC,ZC,DC,PC,DC1,ZC2,DC2,AC3,A3,TW3 ARE
  1.00  2.00  0.00   .75   .20  0.00  0.00  0.00  0.00  2.00  2.00

     CAUTION IWARN = 9
          H/L RATIO IS LESS THAN 0.07
```

Table 2.8--Continued
Output data for example MOVABLE WEIR

WARNING IWARN = 10
GAUGE MAY BE TOO CLOSE TO THROAT

WARNING IWARN = 10
GAUGE MAY BE TOO CLOSE TO RAMP

RATING TABLE MOVABLE WEIR

SILL REFER. HEAD SH1 FT	FLOW RATE Q CFS	FROUDE NO. FR1	H1/TL	DISH. COEFF. CD	VELOC. COEFF. CV	REQ'D HEAD LOSS DH FT	MAX. T-WATER DEPTH Y2 FT	MODULAR LIMIT
.100	.1857	.016	.067	.9492	1.002	.038	1.962	.620
.150	.3486	.031	.100	.9671	1.005	.055	1.946	.636
.200	.5437	.048	.134	.9759	1.009	.070	1.930	.650
.250	.7677	.068	.168	.9808	1.014	.085	1.917	.664
.300	1.0194	.090	.203	.9842	1.021	.098	1.905	.678
.350	1.2977	.114	.238	.9867	1.029	.110	1.895	.691
.400	1.6007	.141	.274	.9868	1.039	.121	1.887	.705
.450	1.9327	.170	.310	.9876	1.051	.131	1.880	.718
.500	2.2946	.202	.348	.9885	1.065	.140	1.875	.731
.550	2.6889	.237	.386	.9892	1.081	.148	1.873	.744
.600	3.1191	.275	.426	.9901	1.100	.155	1.873	.757
.650	3.5911	.317	.468	.9910	1.123	.162	1.876	.770
.700	4.1123	.363	.512	.9919	1.150	.167	1.883	.783
.750	4.6941	.414	.559	.9932	1.183	.172	1.894	.796
.800	5.3545	.472	.611	.9949	1.225	.176	1.910	.808
CAUTION - FROUDE NUMBER GREATER THAN 0.5								
.850	6.1250	.540	.668	.9971	1.279	.179	1.934	.821
CAUTION - FROUDE NUMBER GREATER THAN 0.5								
.900	7.0703	.623	.735	1.0010	1.355	.182	1.970	.835
CAUTION - FROUDE NUMBER GREATER THAN 0.5								
.950	8.3710	.738	.822	1.0100	1.479	.186	2.032	.849

Table 2.8--Continued
Output data for example MOVABLE WEIR

WALL GAUGE DATA   MOVABLE WEIR

FLOW RATE Q CFS	SILL REFER. HEAD SH1 FT	WALL GAUGE DIST. SHS FT
1.00	.296	.296
2.00	.460	.460
3.00	.586	.586
4.00	.689	.689
5.00	.774	.774
6.00	.842	.842
7.00	.896	.896
8.00	.936	.936

DISCHARGE EQUATION   MOVABLE WEIR

EQUATION Q = A * (SH1 +B)**U

Q IN   CFS   SH1 IN FT

COEFFICIENT VALUES

A = 7.455

B = .5000E-01

U = 1.9213

GOODNESS OF FIT

COEFFICIENT OF DETERMINATION (LN) R2 = .998

DATA

SH1 FT	Q CFS	Q(CALC) CFS	ERROR CFS	%ERROR
.100	.1857	.1948	.0090	4.862
.150	.3486	.3385	-.0101	-2.908
.200	.5437	.5197	-.0240	-4.423
.250	.7677	.7377	-.0301	-3.917
.300	1.0194	.9919	-.0275	-2.695
.350	1.2977	1.2820	-.0157	-1.210
.400	1.6007	1.6076	.0069	.429
.450	1.9327	1.9683	.0356	1.840
.500	2.2946	2.3638	.0692	3.018
.550	2.6889	2.7939	.1050	3.905
.600	3.1191	3.2584	.1393	4.465
.650	3.5911	3.7570	.1659	4.618
.700	4.1123	4.2895	.1772	4.309
.750	4.6941	4.8558	.1616	3.444

Table 2.8--Continued
Output data for example MOVABLE WEIR

```
 DATA--Con.
    SHI       Q      Q(CALC)     ERROR   %ERROR
     FT      CFS       CFS       CFS
    .800   5.3545    5.4556     .1010     1.887
    .850   6.1250    6.0888   -.0362     -.590
    .900   7.0703    6.7553   -.3150    -4.455
    .950   8.3710    7.4550   -.9161   -10.943

MW #2                                         TIME = 10:40      DATE =113:1986

CROSS SECTION DATA

   APPROACH CHANNEL
   SIMPLE TRAPEZOID
     BOTTOM WIDTH            B1 =  2.000   FT
     SIDE SLOPE              Z1 =  0.000   : 1

   THROAT SECTION
   SIMPLE TRAPEZOID
     BOTTOM WIDTH            BC =  2.000   FT
     SIDE SLOPE              ZC =  0.000   : 1

   TAILWATER CHANNEL
   SIMPLE TRAPEZOID
     BOTTOM WIDTH            B2 =  2.000   FT
     SIDE SLOPE              Z2 =  0.000   : 1

PROFILE DATA

   MOVABLE WEIR
   ------------
   LENGTH TO GAUGE          AL =  1.000   FT
   CON TRAN RADIUS          RL =   .330   FT
   THROAT LENGTH            TL =  1.500   FT
   DIV RAMP LENGTH         *DL =  0.000   FT
   LENGTH TO SEC 2         *EL = 20.000   FT
   MAXIMUM DEPTH            Y1 =  1.000   FT
   BOTTOM DROP              DP =  1.000   FT
   DIV RAMP SLOPE           EM =  0.000   : 1

   MATERIAL ROUGHNESS       RK =.0005000  FT


     WARNING IWARN = 9    RUN TERMINATED
          HLOW =      .1000 IN     H/L RATIO LESS THAN 0.04
```

3. THEORY

3.1 Introduction

Two approaches can be used to determine the head discharge relationship for flumes and weirs. One is to determine the discharge for an ideal fluid and multiply it by an empirical discharge coefficient, C_d, which is the ratio of the actual to ideal flow.

$$C_d = Q/Q_i \qquad [3.1]$$

The discharge coefficient, C_d, is the result of

1. Friction on the channel wall and bottom between the gauging station and the control section,

2. The velocity profile in the approach channel and control section, and,

3. Changes in pressure distribution caused by streamline curvature.

The other approach is to compute the effects directly by use of a mathematical theory, such as the one presented here. Thus, no empirical discharge coefficient is needed. In either case, the ideal flow is calculated as a base of reference or starting point.

3.2 Ideal Flow Equations

For an ideal fluid at a constant flow, there is only one value of critical depth, y_c, for each value of energy head, H_c:

$$H_c = y_c + A_c/2B_c \qquad [3.2]$$

where

A_c = wetted area at the control section

B_c = water surface width at the control section

As illustrated in figure 3.1, we can write for the gauging station that

$$H_1 = h_1 + Q_i^2/2gA_1^2 \qquad [3.3]$$

where $v_1 = Q_i/A_1$, A_1 = flow area at gauging station (sectional) and g = acceleration of gravity.

For ideal fluid flow, there is no energy loss due to friction over the reach with accelerating flow, and thus $H_c = H_1$, or

$$y_c + A_c/2B_c = h_1 + Q_i^2/2gA_1^2 \qquad [3.4]$$

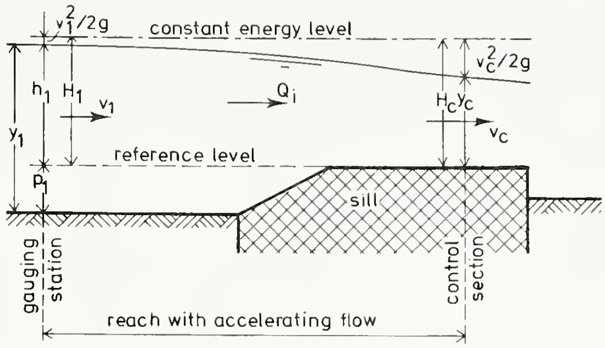

Figure 3.1.
The energy level at the gauging station and the control section for ideal flow.

This equation relates the upstream head h_1 to the ideal flow Q_i for given cross-sectional shapes of the approach channel and the control section.

The ideal flow, Q_i, can also be calculated by

$$Q_i = A_c \sqrt{2g(H_1 - y_c)} \qquad [3.5]$$

in which, according to equations 3.2 and 3.4

$$y_c = H_1 - A_c/2B_c \qquad [3.6]$$

Combining equations 3.5 and 3.6 gives

$$Q_i = \sqrt{g\ A_c{}^3/B_c} \qquad [3.7]$$

This general equation is valid for all arbitrarily shaped control sections. The combined use of equations 3.3, 3.6, and 3.7 is easy if simple equations exist for A_c and B_c in terms of y_c. For a trapezoidal control section, these equations, for example, read

$$A_c = y_c(b_c + z_c y_c) \qquad [3.8]$$

and

$$B_c = b_c + 2z_c y_c \qquad [3.9]$$

The approach channel may also have any shape, but for the usual trapezoidal channel,

$$A_1 = y_1(b_1 + z_1 y_1) \qquad [3.10]$$

where, as shown in figure 3.1,

$$y_1 = p_1 + h_1 \qquad [3.11]$$

Thus, for each combination of approach channel and control section shapes, the equations 3.3, 3.6, and 3.7 have unknown y_c, Q_i, and h_1. If any of these three is given, the other two can be solved by trial and error.

The procedure for this trial and error solution is rather straightforward and starts with determining the range of h_1 values for which the appropriate discharges, Q_i, need to be computed. Next, an initial guess is made for y_c in terms of h_1. The value of y_c ranges from 0.67 H_1 to 0.80 H_1 for a rectangular to a triangular control section respectively. Neglecting the velocity head, $v_1^2/2g$, we guess

$$y_c = 0.70\ h_1 \qquad [3.12]$$

in all first trials. It is not worthwhile to make a better guess of y_c for each computer run, since the trial and error method converges rapidly. Now, once y_c has been guessed, values of A_c, B_c, and Q_i can be computed followed by H_1 and y_c (from computed Q_i value). If the new y_c value equals the input y_c value then the computed Q_i is the flow rate for an ideal fluid matching the set h_1 value. After each trial, the new y_c value replaces the previous y_c.

Using the new y_c value, a new series of calculations is made until the values match. An example of this procedure follows. The procedure is illustrated in figure 3.2.

Example of Ideal Flow Computations

Given. A trapezoidal flume with $b_c = 0.20$ m, $z_c = 1.0$, $p_1 = 0.15$ m, and $L = 0.60$ m is placed in a concrete-lined canal with $b_1 = 0.50$ m and $z_1 = 1.0$.

Question. What is the discharge for an ideal fluid if the upstream sill reference head is $h_1 = 0.238$ m?

Answer. The actual upstream water depth equals (eq. 3.11)

$$y_1 = h_1 + p_1 = 0.238 + 0.150 = 0.388 \text{ m.}$$

The flow area upstream is

$$A_1 = 0.388\ [0.5 + 1.0(0.388)] = 0.345 \text{ m}^2$$

First guess, $y_c = 0.7\ h_1 = 0.167$ m (eq. 3.12)

Then $A_c = y_c(b_c + z_c y_c) = 0.0611 \text{ m}^2$ (eq. 3.8)

$B_c = b_c + 2\ z_c y_c = 0.533$ m (eq. 3.9)

$Q_i = \sqrt{g A_c^3/B_c} = 0.0647 \text{ m}^3/\text{s}$ (eq. 3.7)

$H_1 = h_1 + Q_i^2/(2gA_1^2) = 0.2398$ (eq. 3.3)

new $y_c = H_1 - A_c/2B_c = 0.183$ (eq. 3.6)

$A_c = 0.0698\ m^2$

$B_c = 0.565\ m$

$Q_i = 0.0769\ m^3/s$

$H_1 = 0.2405\ m$

new $y_c = 0.1788\ m$

$A_c = 0.0677\ m^2$

$B_c = 0.558\ m$

$Q_i = 0.0739\ m^3/s$

$H_1 = 0.2403\ m$

new $y_c = 0.1796\ m$

$A_c = 0.0682\ m^2$

$B_c = 0.559\ m$

$Q_i = 0.0746\ m^3/s$

$H_1 = 0.2404\ m$

new $y_c = 0.1794\ m$

$A_c = 0.0681\ m^2$

$B_c = 0.559\ m$

$Q_i = 0.0744\ m^3/s$

$H_1 = 0.2404\ m$

new $y_c = 0.1795\ m$

$A_c = 0.0681\ m^2$

$B_c = 0.559\ m$

$Q_i = 0.0744\ m^3/s$

$H_1 = 0.2404\ m$

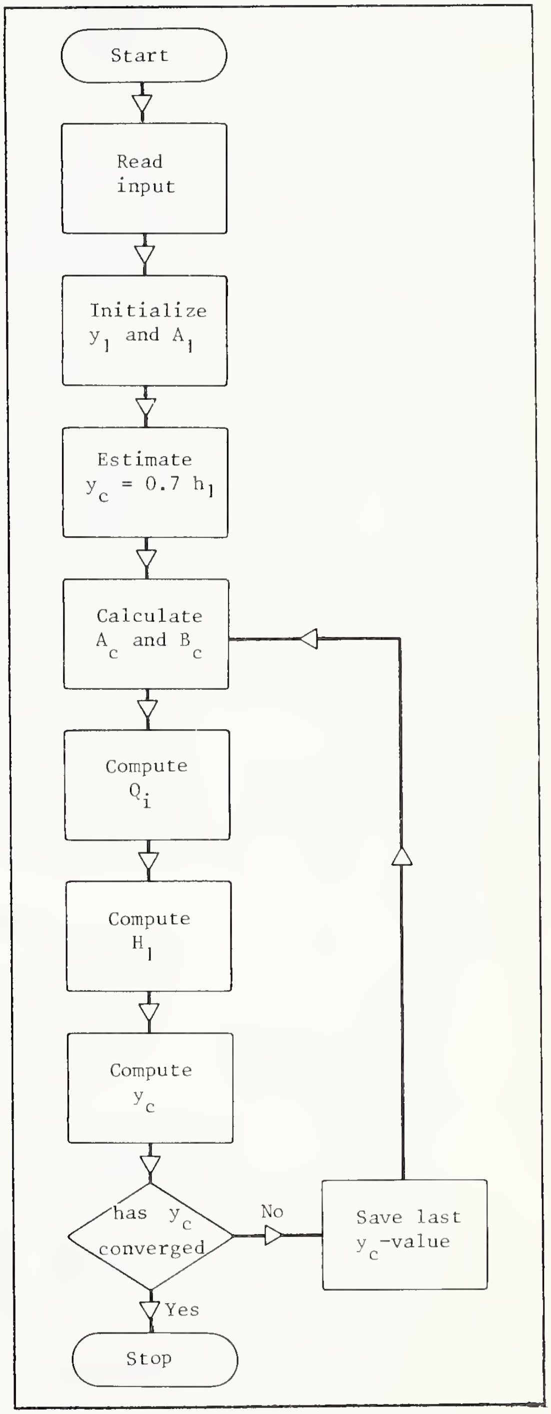

Figure 3.2.
Flow diagram for ideal flow computations.

new y_c = 0.1795 m, which matches the last value of y_c.

Thus, the ideal flow rate, Q_i, is 0.0744 m^3/s.

This method does not require an estimate of the velocity coefficient, C_v, for converting from H_1 to h_1, since both H_1 and h_1 are used in the computation and the energy heads are balanced. Also, the method starts with h_1 rather than H_1, making it useful for the development of stage discharge relationships directly.

3.3. Energy Losses Due to Friction

Because no ideal fluids exist in the real world, we must account for the effects of friction. Evaluating the actual discharge through a flume requires that we account for friction in the approach channel, converging transition, and throat. Friction in the diverging transition and tailwater channel does not affect the flume discharge, but it does affect the tailwater limit for maintaining modular flow (see fig. 3.3).

Several methods are available for estimating friction losses through the flume and are shown in table 3.1. While the functions given are empirical, the boundary layer drag method has some distinct advantages. The Manning Equation is useful for many applications in open channel flow. However, using a constant Manning n for a wide range of flow conditions is unacceptable when precise calibration is necessary. Thus, this approach is not suitable for measuring flumes. Chezy's C and boundary-layer-drag coefficients take into account the absolute roughness height of the flume surface, the kinematic viscosity of the fluid, and the Reynolds number of the flow. The Chezy equation (and the similarly based Darcy-Weisbach equation) however, assumes that the flow is uniform, whereas the boundary

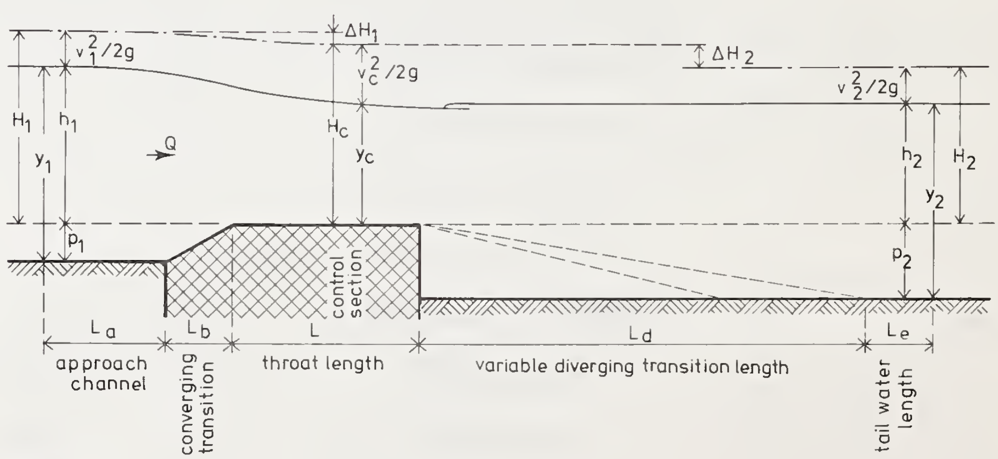

Figure 3.3.
Illustration of terminology.

layer theory would indicate a gradual change in flow conditions. Thus, the boundary layer method is preferred. Ackers and Harrison (1963) reported somewhat better results with the boundary layer method than the friction factor (Chezy) method. Replogle (1975) expanded upon their work and developed a flume model based on boundary layer development, which is presented in this chapter with minor modifications.

The effects of friction could be replaced with a change in flow area represented by an artificial displacement thickness (Harrison 1967). However, this method did not prove as reliable as the boundary layer drag method, which is more appropriate because it is more consistent with the energy-based equations used to determine flow rate.

Table 3.1
Functions for estimating friction or head losses through flume

Function	Equation for head loss	Terminology
		ΔH = head loss due to friction,
Manning	$\Delta H = \dfrac{n^2\ L\ v^2}{C_u^2\ R^{4/3}} = \dfrac{L\ v^2}{R}\ \dfrac{n^2}{C_u^2\ R^{1/3}}$	L = length in direction of flow,
		R = hydraulic radius (area/wetted perimeter),
Chezy	$\Delta H = \dfrac{L\ v^2}{C^2\ R} = \dfrac{L\ v^2}{R}\ \dfrac{1}{C^2}$	C = Chezy C,
		n = Manning n,
		C_u = units coefficient for the Manning n,
Boundary layer drag	$\Delta H = \dfrac{C_F\ L\ v^2}{R\ 2g} = \dfrac{L\ v^2}{R}\ \dfrac{C_F}{2g}$	v = average flow velocity,
		g = acceleration of gravity
		C_F = drag coefficient.

3.3.1. Boundary Layer Theory

For the boundary layer analysis, it is assumed that the throat of the flume is one side of a thin and smooth flat plate held parallel to the fluid flow. The plate causes a drag on the fluid, which results in energy or head losses. The boundary layer is assumed to be "tripped" by the break between the converging transition and the throat. Boundary layer theory indicates that the flow in the boundary layer is not constant but varies along the plate. The boundary layer starts out as laminar flow and then develops into turbulent flow, as shown in figure 3.4. In reality, the transition from laminar to turbulent flow is gradual. For computing drag, however, the transition is assumed to be abrupt and to occur at a distance, L_x, from the entrance to the throat.

The combined drag coefficient, C_F, can be found by adding the relative drag coefficients for the laminar and turbulent parts of the boundary layer (Schlichting 1960). The turbulent part of the boundary layer acts as if the entire boundary layer were turbulent; thus the drag coefficient for the nonexistent turbulent boundary layer over L_x, namely $C_{F,x}$, must be subtracted from the turbulent drag coefficient over L, $C_{F,L}$. The combined drag coefficient is then

$$C_F = C_{F,L} - \frac{L_x}{L} C_{F,x} + \frac{L_x}{L} C_{f,x} \qquad [3.13]$$

where $C_{f,x}$ is the coefficient for the laminar boundary layer over L_x. The distance L_x can be developed from an empirical relationship for the Reynolds number of the laminar portion of the boundary layer.

$$Re_x = 350000 + L/k \qquad [3.14]$$

where k = absolute roughness height of the material. This Reynolds number is related to L_x by the definition

$$Re_x = v_c L_x/\nu \qquad [3.15]$$

where $v_c = Q/A_c$ = average velocity of flow and ν = the kinematic viscosity of the fluid. Similarly, the Reynolds number over the entire length L is

$$Re_L = v_c L/\nu \qquad [3.16]$$

Values for the turbulent drag coefficients are found from the following relationship (Harrison 1967), which was derived from Granville (1958)

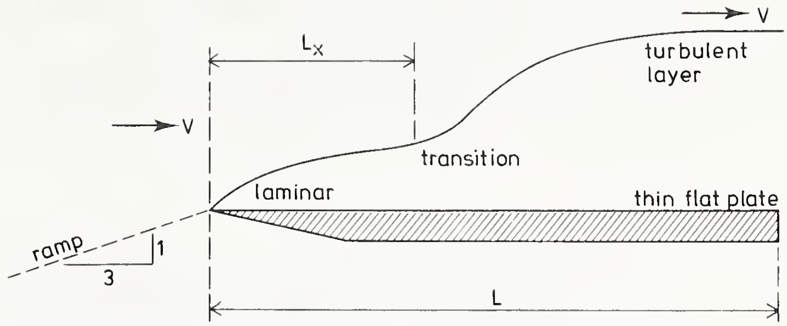

Figure 3.4.
Transition from laminar to turbulent boundary layer.

$$C_{F,L} = 0.544\ C_{F,L}^{0.5}/\{5.61\ C_{F,L}^{0.5} - 0.638 - \ln[(Re_L C_{F,L})^{-1} + (4.84\ C_{F,L}^{0.5}\ L/k)^{-1}]\} \qquad [3.17]$$

Equation 3.17 can be used to determine $C_{F,x}$ by replacing $C_{F,L}$, Re_L and L with $C_{F,x}$, Re_x and L_x. This equation must be solved by trial and error, since $C_{F,L}$ (or $C_{F,x}$) appears several times.

The drag coefficient for laminar flow can be computed by the following equation suggested by Schlichting (1960):

$$C_{f,x} = 1.328/Re_x^{0.5} \qquad [3.18]$$

If $Re_L < Re_x$, then the entire boundary layer is laminar and $C_F = C_{f,L}$, which is found from equation 3.18 with Re_L replacing Re_x.

For a fully developed turbulent boundary layer, as would be expected in the approach channel, converging transition, diverging transition, and tailwater channel (see fig. 3.3), the drag coefficient can be taken as 0.00235. The head loss for each part of the flume is found from the following equation (table 3.1):

$$\Delta H_L = \frac{C_F L}{R} \frac{v^2}{2g} \qquad [3.19]$$

where L is the length of each part considered, and R is the hydraulic radius (area/wetted perimeter). The combined head loss of the approach channel, converging transition, and throat is subtracted from the energy head at the gauging station to

give the energy head in the critical section, $H_c = H_1 - \Delta H_1$. Equation 3.6 changes to

$$y_c = H_1 - A_c/2B_c - \Delta H_1 \qquad [3.20]$$

where

$$\Delta H_1 = \Delta H_a + \Delta H_b + \Delta H_L \qquad [3.21]$$

and the ΔH_a, ΔH_b, and ΔH_L correspond to the head losses in the approach channel, converging transition, and throat, respectively.

3.3.2 Roughness of Construction Materials

The absolute roughness height for a number of materials typically used for flume construction is given in table 3.2. An analysis of the effects of roughness height showed that a change of several orders of magnitude in the value of k produces less than an 0.5-percent (and often less than 0.1-percent) change in discharge. Thus, a change in use of materials from smooth glass to rough concrete will have a minor effect on the discharge rating. This minor effect, however, should not be used as an excuse for sloppy or poor construction. If the surfaces in the control section have large undulations and irregularities, the resulting discharge can be considerably in error. Material roughness and construction tolerances should be considered as different sources of potential error.

Table 3.2
Absolute roughness height of materials used in flume construction

Material	Range of k [1] Absolute Roughness Height in (m)
Glass	0.000001 - 0.000010
Metal - painted or smooth	.000020 - .000100
- rough	.000100 - .001000
Wood	.000200 - .001000
Concrete - smooth troweled	.000100 - .002000
- rough	.000500 - .005000

1 In program, k = RK.

3.3.3. Friction and Other Effects on the Range of H_1/L

A limitation was placed on the range of H_1/L values for which a reasonably reliable discharge rating can be obtained when an empirical discharge coefficient is used, namely,

$$0.1 \leqslant H_1/L \leqslant 1.0 \qquad [3.22]$$

This limitation was based on extensive laboratory data on a wide variety of flumes made from a variety of construction materials (See Bos 1978). Within the range delimited by equation 3.22, a good estimate of the discharge can be made from an empirical curve through the data. The data appear more closely grouped in the middle range (H_1/L = 0.35 to 0.75) with ± 3 percent for the 95-percent confidence limits and more widely scattered at the extremes (H_1/L = 0.1 and H_1/L = 1.0) with ± 5 percent for the 95-percent confidence limits. One of the major reasons for the wide scatter of data in the low range is friction. The computer model presented in this chapter can accurately account for frictional effects even when the value of H_1/L is as low as 0.05. One major reason for the wide scatter of data at the high range of H_1/L is streamline curvature. The laboratory data appear to deviate from the computer predictions above an H_1/L value of about 0.5 due to streamline curvature, making the practical range of applicability of the computer model

$$0.05 \leqslant H_1/L \leqslant 0.5 \qquad [3.23]$$

A compromise can be reached between the two ranges to give a fairly realistic discharge range. Two factors are the basis of this compromise. First, the roughness of the construction materials changes over time. At low H_1/L values, these roughness changes can have a major influence on the flume calibration. Thus, while the model can predict these effects down to H_1/L = 0.05, possible changes in roughness restrict ordinary use of the model to $H_1/L \geqslant 0.075$. Up to H_1/L = 0.75, the effects of streamline curvature are minimal and have little effect on the discharge coefficient. A reasonable compromise between the two ranges for H_1/L, therefore, is

$$0.075 \leqslant H_1/L \leqslant 0.75 \qquad [3.24]$$

which we recommend.

3.4. Velocity Profiles

The equations for ideal flow developed earlier in this chapter assume that the velocity profile in the throat is uniform. It may not be uniform, however, and so a velocity-distribution coefficient, α, is introduced to account for non-uniform velocity profiles. The value of α is the ratio between the actual

velocity head of the flow and the velocity head based on the average velocity of the flow, and it is always greater than one. In long prismatic channels with a fully developed flow profile, α approaches a value of roughly 1.04 (Watts et al. 1967). For the approach channel, the velocity profile is assumed to be fully developed. This approximate value of α_1 = 1.04 is used without further adjustment since the error in energy head resulting from an error in α_1 or the velocity head is relatively small. For the control section, the velocity head is a much larger percentage of the total energy head, and the velocity distributions for critical flow tend to be more uniform. Thus, some correction for α_c at the control section is warranted. The following equation has been developed to estimate α for fully developed flow in wide channels (Chow 1959):

$$\alpha = 1 + 3\,\varepsilon^2 - 2\,\varepsilon^3 \qquad [3.25]$$

where $\varepsilon = (v_m/v)-1$ with v_m = the maximum flow velocity. For fully developed flow, ε can be approximated by

$$\varepsilon = 1.77\, C_{F,L}^{0.5} \qquad [3.26]$$

At the control section, the channel may not be sufficiently wide, and the flow profile may not be fully developed. Two additional factors are added to equation 3.25 to account for these deficiencies (Replogle 1974):

$$\alpha_c = 1 + [3\varepsilon^2 - 2\varepsilon^3][1.5(D/R)-0.5][0.025(L/R)-0.05] \qquad [3.27]$$

with $1 \leqslant [1.5(D/R)-0.5] \leqslant 2$

and $0 \leqslant [0.025(L/R)-0.05] \leqslant 1$

where D is the average or hydraulic depth and the other terms are as previously defined. This equation results in velocity distribution coefficients ranging from 1.00 to 1.04 for the ranges of conditions typically found in practice. This range is realistic, since several investigators have found nearly uniform velocity profiles at the control sections of long-throated flumes (see figure 3.5).

With the addition of the velocity distribution coefficient, equation 3.7 becomes

$$Q = \sqrt{gA_c^3/\alpha_c B_c} \qquad [3.28]$$

and equation 3.3 becomes

$$H_1 = h_1 + \alpha_1 Q^2/(2gA_1^2) \qquad [3.29]$$

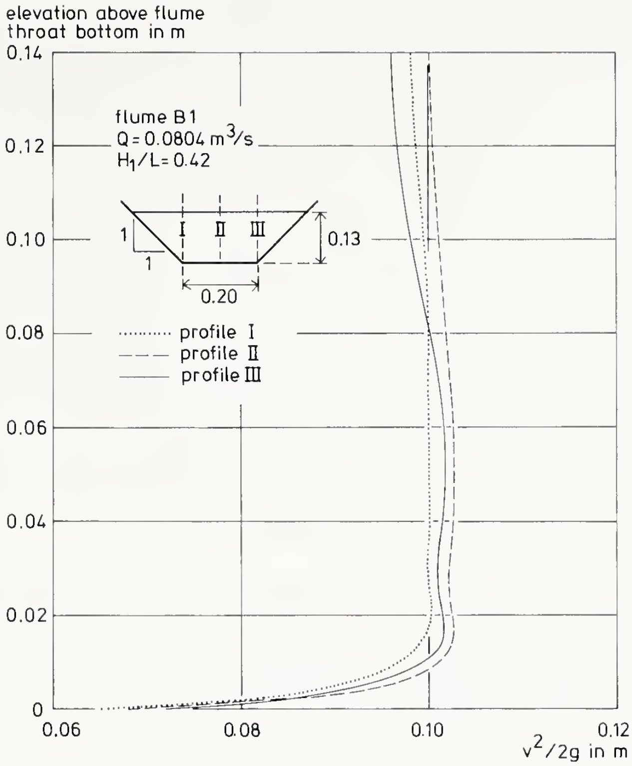

Figure 3.5.
Velocity distribution in the control section of a long-throated flume (from Bos and Reinink 1981).

where $\alpha_1 \simeq 1.04$ and α_c is found from equation 3.27. The equations for the hydraulic radii of the different sections are

$$
\begin{aligned}
R_1 &= A_1/(b_1 + 2\, y_1\sqrt{1 + z_1^2}) \\
R_b &= A_b/(b_c + 2\, y_b\sqrt{1 + z_b^2}) \qquad [3.30] \\
R_c &= A_c/(b_c + 2\, y_c\sqrt{1 + z_c^2}) \\
R_2 &= A_2/(b_1 + 2\, y_2\sqrt{1 + z_2^2})
\end{aligned}
$$

where the subscript b refers to the entrance to the flume throat (that is, entrance has same cross section shape as throat, but greater depth; see eq. 3.33). The equations for the hydraulic depths are

$$D_1 = A_1/B_1 \qquad [3.31]$$

$$D_c = A_c/B_c$$

3.5. Computing Actual Flow

Actual flow rates are computed by the same procedures that were used for ideal flow rates except that equations 3.20, 3.28, and 3.29 replace equations 3.6, 3.7, and 3.3, respectively. Values for ΔH_L are obtained from equations 3.13 to 3.19, and the value for α_c is found from equation 3.27. The ideal flow rate is computed first and is used as the initial guess for the actual flow rate. Next, the friction losses and velocity distribution coefficients are computed for the estimated discharge. Then, the actual flow rate (equation 3.28) and the critical depth (equation 3.20) are computed. The trial and error process is repeated (as for the ideal flow rate) until y_c converges. The resulting flow rate is checked against the flow rate for the previous values of ΔH_L and α_c. (The first time through, it will be compared with the ideal Q_i.) If the flow rate has not converged, ΔH_L and α_c are computed with the new Q and the process is repeated until the flow rate converges. This procedure is illustrated in figure 3.6.

3.5.1. Example of Actual Flow Computations

Given. The same conditions as in the example for ideal flow where the ideal flow is $Q_i = 0.0744$ m^3/s, $h_1 = 0.238$ m, and $y_c = 0.1795$ m with $k = 0.0002$ m, $\nu = 1.14 \times 10^{-6}$ m^2/s, $L_a = 0.5$ m, and $L_b = 0.45$ m.

Question. What is the actual discharge, Q?

Answer. Since the ideal flow has already been calculated, the friction losses and velocity distribution coefficient are computed first; then flow is computed.

<u>Friction losses.</u> $v_c = Q/A_c = 0.0744/0.0681 = 1.0925$ m/s

$$Re_x = 350{,}000 + L/k = 350{,}000 + 0.60/0.0002 = 353{,}000 \quad \text{(eq. 3.14)}$$

$$Re_L = v_c\, L/\nu = (1.0925)(0.60)/(1.14 \times 10^{-6}) \quad \text{(eq. 3.16)}$$

$$= 575{,}000$$

$$L_x = Re_x\, \nu/v_c = 0.368 \text{ m} \quad \text{(eq. 3.15)}$$

$$C_{f,x} = 1.328/Re_x^{0.5} = 0.00224 \quad \text{(eq. 3.18)}$$

To find $C_{F,L}$ from equation 3.17, an initially guessed value of $C_{F,L} = 0.005$ is substituted into the right-hand part of this equation, which gives as a next value

$$C_{F,L} = \frac{0.0385}{0.397 - 0.638 - \ln[0.00035 + 0.00097]} = 0.00602$$

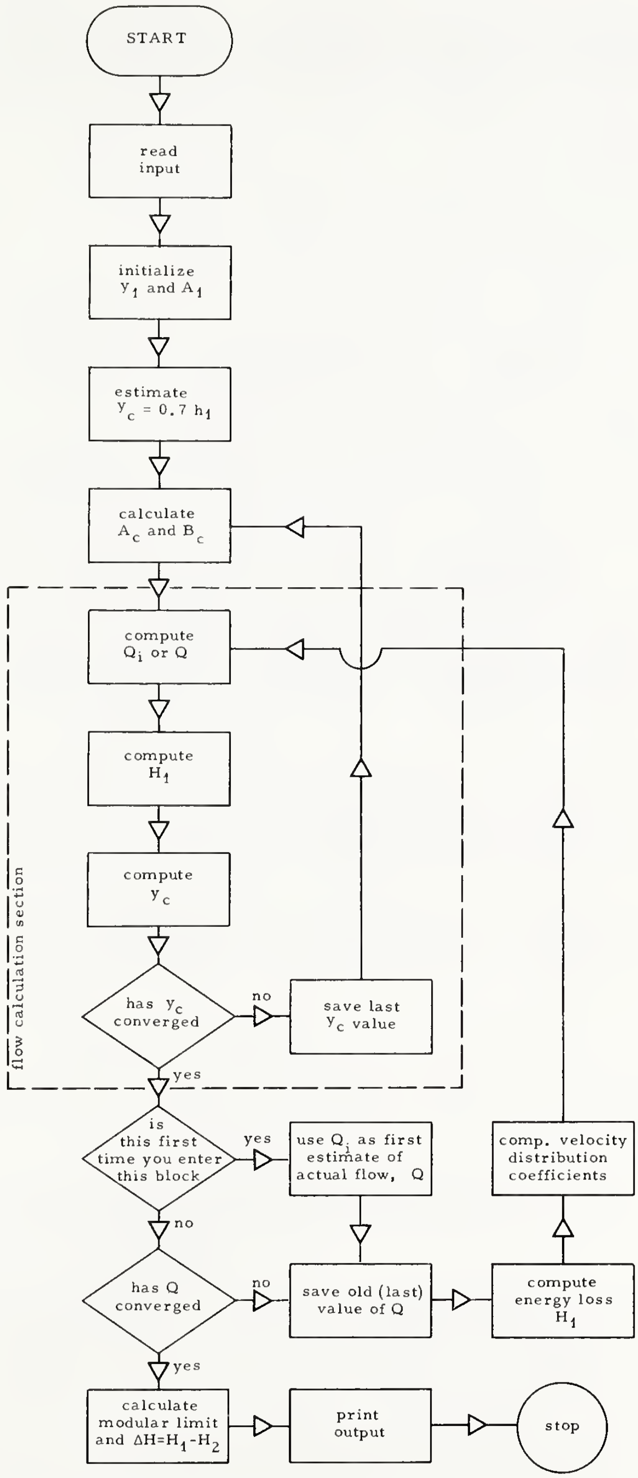

Figure 3.6.
Flow diagram for computing discharge and modular limit.

Another iteration gives $C_{F,L} = 0.00645$, which eventually converges to 0.00672. Repeating the procedure for $C_{F,x}$, with L_x and Re_x replacing L and Re_L, gives $C_{F,x} = 0.00652$, which converges to 0.00758. The combined drag coefficient is found from Equation 3.13:

$$C_F = C_{F,L} - \frac{L_x}{L} C_{F,x} + \frac{L_x}{L} C_{f,x}$$

$$= 0.00672 - \frac{0.368}{0.6}(0.00758 - 0.00224) = 0.00344$$

For the flume throat, the hydraulic radius R_c is (eq. 3.30)

$$R_c = A_c/(b_c + 2\, y_c\sqrt{1 + z_c^2}) = 0.0681/0.708 = 0.0962 \text{ m}$$

The friction loss over the throat is (eq. 3.19)

$$\Delta H_L = \frac{C_F\ L\ v_c^2}{2g\ R_c} = \frac{(0.00344)(0.60)(1.0925)^2}{2(9.81)(0.0962)} = 0.00131 \text{ m}$$

(Note that the entire length, L, is used rather than the distance to the control section, since the location of the control section is variable).

For the approach channel, $C_F = 0.00235$, and $v_1 = Q/A_1 = 0.216$ m/s. The hydraulic radius is (eq. 3.30)

$$R_1 = A_1/(b_1 + 2\, y_1\sqrt{1 + z_1^2}) = 0.216 \text{ m}$$

The friction loss in the approach channel is (eq. 3.19)

$$\Delta H_a = \frac{C_F\ L_a\ v_1^2}{2g\ R_1} = \frac{(0.00235)(0.50)(0.216)^2}{2(9.81)(0.216)} = 0.00001 \text{ m}$$

For the converging transition, the head loss is calculated from the average drag, or

$$\Delta H_b = \frac{0.00235\ L_b}{4g}(v_1^2/R_1 + v_b^2/R_b) \qquad [3.32]$$

where v_b and R_b are the velocity and hydraulic radius at the entrance to the throat section where the depth is approximated by

$$y_b = y_c + \frac{5}{8}(h_1 - y_c) \qquad [3.33]$$

$$= 0.1795 + \frac{5}{8}(0.238 - 0.1795) = 0.216 \text{ m}$$

Because section b has the same cross section as the flume throat, $A_b = 0.0899\ m^2$, $v_b = 0.828$ m/s, $R_b = 0.111$ m. Then,

$$\Delta H_b = \frac{0.00235\ (0.45)}{4\ (9.81)} \left\{\frac{(0.216)^2}{0.216} + \frac{(0.828)^2}{0.111}\right\} = 0.00017 \text{ m}$$

The total head loss from equation 3.21 is

$$\Delta H_1 = \Delta H_a + \Delta H_b + \Delta H_L = \underline{0.00149 \text{ m}}$$

<u>Velocity distribution coefficient</u>. For the approach channel, $\alpha_1 = 1.04$. For the throat, α_c is found through a series of calculations, the first of which is (eq. 3.26)

$$\varepsilon = 1.77\sqrt{C_{F,L}} = 0.145$$

Next, the average or hydraulic depth is calculated as the area divided by the top width (eq. 3.31)

$$D_c = A_c/B_c = 0.0681/0.559 = 0.122 \text{ m}$$

Then, the known values are substituted into equation 3.27 giving:

$$\alpha_c = 1 + [3\varepsilon^2 - 2\varepsilon^3][1.5(D_c/R_c) - 0.5][0.025(L/R_c) - 0.05]$$

$$= 1 + [3(0.145)^2 - 2(0.145)^3][1.5(0.122/0.0962) - 0.5]$$

$$[0.025(0.6/0.0962) - 0.05]\ \alpha_c$$

$$= 1.0085$$

<u>Flow</u>. The process for computing the ideal flow is repeated, except that values for ΔH_1, α_1, and α_c are added to the equations. A new estimate of Q is made from equation 3.28

$$Q = \sqrt{g\ A_c^3/\alpha_c B_c} = \sqrt{(9.81)(0.0681)^3/(1.0085)(0.559)}$$

$$= 0.0741\ m^3/s$$

Then, the upstream energy head, H_1, is computed from equation 3.29

$$H_1 = h_1+\alpha_1 Q^2/2gA_1{}^2 = 0.238+1.04(0.0741)^2/2(9.81)(0.345)^2$$

$$= 0.2405 \text{ m}$$

Then compute a new estimate of y_c from equation 3.20.

$$y_c = H_1-A_c/2B_c-\Delta H_1 = 0.2405-0.0681/2(0.559)-0.00149$$

$$= 0.1781 \text{ m}$$

The same iteration procedure is used until y_c converges. In this case y_c converges to 0.1783 m, and the corresponding Q = 0.0732 m^3/s.

The iteration loop for Q is continued. The new estimates for y_c and Q are used to recompute the friction loss and velocity distribution coefficient. These computations result in C_F = 0.00343, ΔH_1 = 0.00147, and α_c = 1.0085. The process is repeated, giving Q = 0.0732 m^3/s and y_c = 0.1783 m. Thus, the solution converges very rapidly. The resulting discharge coefficient is (equation 3.1)

$$C_d = 0.0732/0.0744 = 0.984$$

3.5.2. Accuracy of Computed Flow Rates

Laboratory tests have shown that the computer model precictions are within $\pm$ 2 percent of actual discharge for the range of conditions specified (see Replogle 1978). The model does not account for field measurement errors, either in flume dimensions (including head detection) or in the flow rate determined by separate means.

The ideal flow equations developed in section 3.2 are inadequate for determining the actual rate of flow, as shown by the preceding example. The differences between actual and ideal flow result primarily from the effects of fluid viscosity (friction, velocity distributions, shape effects, and so on) and the nonhydrostatic pressure distributions that result from streamline curvature. These effects can be handled with a discharge coefficient, C_d. The range of C_d is limited by the increasingly wide scatter both at low H_1/L values resulting from friction and at high H_1/L values resulting from streamline curvature. The laboratory (and field) data scatter for the relationship between C_d and H_1/L results from: (1) the scale effects associated with viscosity, (2) streamline curvature (which is affected by cross section shape and flow conditions

in the diverging transition), and (3) laboratory measurement errors. The data scatter due to laboratory measurement errors results from inaccurate dimensions (for example, deflection of laboratory flumes due to water weight), inaccurate zero setting or head detection, or inaccurate determination of discharge.

In this chapter, we have presented a mathematical model which attempts to correct for the scale effects associated with viscosity. No attempt is made to account for streamline curvature or measurement errors. The effects of streamline curvature are minimized by limiting the range on H_1/L (see section 3.3.3).

The ability of mathematical models to accurately predict physical processes is limited to the accuracy of the descriptive equations and related coefficients. Whenever possible, or reasonably practical, the models are based on fundamental physical principles with coefficients that have well defined responses to environmental conditions. Such principles and coefficients are the basis of the model presented here.

Replogle (1978) reported calibrations on 17 long-throated flumes that had triangular, rectangular, and trapezoidal throats and that were rated against a weigh-tank-and-beam scales system with a maximum weight capacity of about 7000 kg. He obtained good agreement with the model within approximately ±2 percent. In all cases deviations greater than 1 or 2 percent were attributable to specific causes, such as structural deflection or head detection errors. Field calibrations with current meters on larger structures have also been reported by Replogle (1975, 1978) and Replogle et al. (1983). In all cases the comparisons supported the validity of the model well within the accepted error of the comparison method. These comparisons are cited to support the claim that the model predictions are within ± 2 percent. Again, this error does not include undetected dimensional and zero registration errors. Further refinements could probably be made on the model to increase accuracy, but these may require additional field data (such as a better estimate of the approach velocity distribution coefficient, α_1). Because the accuracy of the model is greater than most field accuracy requirements, such additional modifications are probably unjustified, particularly if they require additional analysis of site-specific conditions.

3.6 Determining Acceptable Tailwater Levels

Maintaining modular flow requires that the energy head downstream from the structure be somewhat less than the energy head in the critical section for any given discharge. The energy head downstream is controlled by the channel conditions and structures downstream. Therefore, the flume must be designed so that the energy head in the critical section (and the approach channel) is high enough to assure modular flow.

The modular limit is the highest ratio between downstream and upstream energy head referenced to the flume sill or crest at which the flow is still modular, that is, where the upstream head-discharge relation is not affected by downstream conditions. In section 3.3, methods were given for determining the head or energy loss from the gauging station to the end of the flume throat. In this section, we will discuss the energy losses downstream from the flume throat. These energy losses are from two types: 1) frictional losses, and 2) turbulent losses caused by the rapid expansion of flow. The frictional energy losses downstream from the flume throat are relatively small compared with the turbulent energy losses. Thus, some rough approximations are sufficient. The frictional energy losses can be estimated with sufficient accuracy by boundary layer drag methods as discussed in section 3.3.1. Just as for the approach channel, a constant drag coefficient of 0.00235 can be used. No information is available from which to estimate α_2, and since it also has little effect compared with the turbulent energy losses it is assumed equal to unity. The total energy loss over the downstream part of the structure is

$$\Delta H_2 = \Delta H_d + \Delta H_e + \Delta H_k = \Delta H_f + \Delta H_k \qquad [3.34]$$

where ΔH_f is the frictional loss downstream from the structure, ΔH_d is the frictional loss over the downstream transition, ΔH_e is the frictional loss over part of the tailwater channel, and ΔH_k is the energy loss due to the rapid expansion. The frictional losses are computed with equation 3.19.

The energy loss or conversion for the downstream expansion (diverging transition) is

$$\Delta H_k = \xi \, (v_c - v_2)^2/2g \qquad [3.35]$$

where ξ can be obtained from (adapted from Bos and Reinink 1981)

$$\xi = \frac{\log_{10}[114.59 \mathrm{Arctan}(1/m)] - 0.165}{1.742} \qquad [3.36]$$

where Arctan is in radians and m is the expansion ratio as previously defined.

For a flume with only a bottom contraction, such as the broad-crested weir, the expansion ratio is straightforward. It is simply the length of the transition divided by the sill height. For flumes with a side contraction or a combination of a side contraction and a bottom contraction, determining a value for

the expansion ratio is not quite as straightforward. The expansion of the flume bottom has a greater effect on the energy loss and recovery than the side contraction. Thus, for flumes with a sizable bottom contraction, the expansion of the bottom should be used in head loss calculations. When the contraction is primarily from the side, then the expansion ratio for the side walls should be used. Obviously, in some cases, both play a role. For these cases, there is no clear-cut way of determining which to use. However, observed data indicate that the values of ξ from equation 3.36 are conservative and can be used for most flumes. The minimum value of the side and bottom contraction ratios should be used.

The flume designer would usually like to find the maximum tailwater level and energy head, H_2, for which modular flow exists. These are found by solving for the minimum amount of energy loss through the structure. By solving for H_2 we obtain (see figure 3.3):

$$H_2 = H_c - \Delta H_f - \Delta H_k = H_c - \Delta H_2 \quad [3.37]$$

$$= H_1 - \Delta H_1 - \Delta H_2$$

The friction loss in the throat downstream from the control section is contained in ΔH_1 rather than H_f. Thus, H_f includes only the friction losses in the diverging transition and tailwater channel. For a given flume with a known expansion ratio, channel geometry, upstream head, and flow rate, H_c and ΔH_f can be computed by the procedures given in sections 3.2 to 3.4. Since the flow rate and channel geometry are known, v_2 and thus H_2 and ΔH_e are functions of h_2. Therefore, equation 3.37 can be solved by trial and error with one unknown, h_2. The modular limit is then computed as

$$ML = H_2/H_1 \quad [3.38]$$

Example

Given. The example of section 3.2. (where h_1 = 0.238 m and Q = 0.0732 m^3/s), with a 6:1 downstream expansion (m = 6), $p_1 = p_2$, $b_1 = b_2$, and $z_1 = z_2$.

Find. The required head loss, ΔH, over the flume and the modular limit, H_2/H_1 for both the given expansion and a rapid or sudden expansion.

Solution. The maximum tailwater level, H_2, referenced to the flume sill is found from equation 3.37. From the previous example, H_1 = 0.2404 m, ΔH_1 = 0.000147 m. A value for ΔH_2 (or ΔH_f and ΔH_k) is found from Equation 3.34, as follows:

Downstream frictional losses. The frictional losses of energy downstream from the structure are found from equation 3.19, with $C_F = 0.00235$ and v and R calculated from flow rate and cross sectional shape. For this flume, it is reasonable to assume that the bottom contraction dominates the energy losses. The length of the diverging transition is found from

$$L_d = p_2 \, (m) = (0.15)(6) = 0.9 \text{ m} \qquad [3.39]$$

A reasonable length downstream from the structure is provided by

$$L_e = 10 \left(p_2 + \frac{L}{2}\right) - L_d \qquad [3.40]$$

$$= 10 \, (.15 + .3) - 0.9 = 3.6 \text{ m}$$

This assures that H_2 is measured at a point far enough downstream from the end of the diverging transition such that the water surface is reasonably stable and not so far downstream that friction losses are unreasonably high.

A trial and error process is required to obtain the maximum value of H_2. A reasonable initial estimate for h_2 is $h_2 = h_c$. For the tail-water channel in this example

$$y_2 = h_2 + p_2 = 0.1783 + 0.15 = 0.3283 \text{ m}$$

$$A_2 = y_2(b_2 + z_2 y_2) = 0.272 \text{ m}^2$$

$$v_2 = Q/A_2 = 0.269 \text{ m/s}$$

$$R_2 = A_2/(b_2 + 2\, y_2\sqrt{1 + z_2^2}\,) = 0.190 \text{ m}$$

Substitution of these values into equation 3.19 yields

$$\Delta H_e = \frac{0.00235\, L_e\, v_2^2}{2g\, R_2} = \frac{0.00235(3.6)(0.269)^2}{(2)(9.81)(0.190)} = 0.00016 \text{ m}$$

For the diverging transition, the head loss due to friction is found from the average drag by (eq. 3.32):

$$\Delta H_d = \frac{0.00235\, L_d}{4g} \left(v_c^2/R_c + v_2^2/R_2\right)$$

where it is assumed that v_c and R_c approximately represent the conditions at the downstream end of the throat. Thus

y_c = 0.1783 m from previous example

$A_c = y_c\ (b_c + z_c y_c) = 0.0675\ m^2$

$v_c = Q/A_c = 1.084$ m/s

$R_c = A_c/(b_c + 2y_c\sqrt{1 + z_c^2}) = 0.096$ m

$$\Delta H_d = \frac{0.00235\ (0.9)}{4(9.81)}\ ((1.09)^2/0.096 + (0.269)^2/0.190)$$

$$= 0.00068 \text{ m}$$

Adding the two friction losses yields

$$\Delta H_f = \Delta H_d + \Delta H_e = 0.00084 \text{ m}$$

Expansion losses. The expansion losses can be computed directly from Equation 3.35 and 3.36, respectively

$$\xi = \{\log_{10}[114.59 \text{ Arctan } (1/m)] - 0.165\}/1.742$$

$$= \{\log_{10}[114.59 \text{ Arctan } (1/6)] - 0.165\}/1.742$$

$$= \{\log_{10}[114.59(0.1651 \text{ radians})] - 0.165\}/1.742$$

$$= 0.64$$

Substituting all values into equation 3.36 gives

$$\Delta H_k = \xi\ \frac{(v_c - v_2)^2}{2g} = \frac{0.64(1.084 - 0.269)^2}{2(9.81)} = 0.0217 \text{ m}$$

The total head loss, ΔH_2, is

$$\Delta H_2 = \Delta H_f + \Delta H_k = 0.00084 + 0.0217 = 0.0225 \text{ m}$$

Check energy balance. From the above calculations, the first trial value, H_{2T}, for the downstream energy head, H_2, is

$$H_{2T} = H_1 - \Delta H_1 - \Delta H_2 = 0.2404 - 0.00147 - 0.0225$$

$$= 0.2164 \text{ m}$$

The estimated H_2 is

$$H_2 = h_2 + v_2^2/2g = 0.1783 + (0.269)^2/(2 \cdot 9.81)$$

$$= 0.1820 \text{ m}$$

Thus, our initial guess for h_2 was too low. A new trial run is made after a new guess of y_2 is made by substituting the old values into the right-hand part of the following equation:

$$y_2(\text{new}) = y_2 \frac{(H_{2T} + p_2)}{(H_2 + p_2)} = 0.3623 \text{ m} \qquad [3.41]$$

This equation gives good estimates of y_2, since $v_2{}^2/2g$ is small with respect to y_2.

The entire process is repeated until the energy head, H_2, is balanced. This occurs at $\Delta H_2 = 0.0243$ m, $H_2 = 0.2146$ m, $y_2 = 0.3618$ m, and $h_2 = 0.2118$ m. The modular limit is then

$$ML = H_2/H_1 = 0.2146/0.2404 = 0.893$$

with

$$\Delta H = H_1 - H_2 = 0.026 \text{ m}$$

Rapid expansion. For a rapid expansion, $L_d = 0$, $\Delta H_d = 0$, $\Delta H_f = \Delta H_e$, and $\xi = 1.2$. The following values are computed

$\Delta H_e = 0.0002$ m

$\Delta H_k = 0.0408$ m

$\Delta H_2 = 0.0410$ m

$H_{2T} = 0.1980$ m

$H_2 = 0.1820$ m

This finally converges to

$\Delta H_2 = 0.0426$ m

$H_2 = 0.1964$ m

$y_2 = 0.3431$ m

$h_2 = 0.1931$ m

$ML = 0.817$ m

$\Delta H = 0.044$ m

The sudden or rapid expansion changed the minimum head loss, ΔH, from 0.026 m to 0.044 m, or by an increment of about 0.02 m. Whether this 0.02 m additional head loss is created by raising the weir sill (crest) or whether the expansion 6:1 is constructed must be decided for each structure. The decision depends on such factors as availability of rating tables, available head loss (freeboard), and construction cost of alternative structures.

In this context, the reader must note that the hydraulic roughness of a canal embankment changes with the age of the construction material, the seasons, and so forth. To avoid nonmodular flow through the weir or flume, the hydraulic roughness of the downstream channel must be maximized to find the lowest expected value of v_2 and highest related water depth, y_2.

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Two versions of the computer program are available. The first is set up for operation on a Hewlett Packard (HP) 1000 Series B, RTE VI Fortran IV or Fortran 77 compiler. The first page of that program version is an expanded memory (EMA) listing. Data statements in this section should be moved to the main program if used on another computer system. The second program version is written for operation on personal computers with Microsoft Fortran 77. The input and output device numbers are: II = input device number for data, IO = output device number for output data, IT = terminal device number for queries. IFL1 through IFL4 are the output files described in the following paragraphs.

The data for the original rating table can be output for plotting to File IFL1, which is specified by the user in input line 12A. Note that when F1 in input Line 12 is not input as "1", then no file is opened and no data are stored. (The file is opened approximately on line 648 and closed on line 691 of the HP version of the main program.) The flume input data are not written to this file, only (a) the user input run description, (b) the constants which indicate the flume dimensions and output units, IOPT1, JOPT1, JOPT2, (format 3I5), and (c) the columns from the output table with headings (2 lines). The only difference between this output (as shown in table A1) and that sent to the standard output device is that the downstream depth for the plotting file is the sill-referenced depth $h_2 = y_2 - p_2$ rather than the actual depth y_2.

The data from the inverse rating table (wall gauge data) is output for plotting wall gauges to file IFL2, which is specified by the user in input line 10B. This file is opened on approximately line 1153 (and closed on line 1262) of subroutine "GAUGE," which again is skipped if the file is not requested in input line 12. Data output to this file inclulde: (a) user's run description from input line 2, (b) a line containing IOPT1, JOPT1, JOPT2 (format 3I5), which are the unit's systems input by the user in input lines 3 and 10, (c) column headings (2 lines), and (d) the remaining data lines containing discharge and the corresponding sloping (for a trapezpidal shape) or vertical (for any other shape) distance values. The output file for example FLUME #7 is given in table A2.

File IFL3 is an input data file for reading field or laboratory data. The data should be in two columns for h_1 and Q and are read free-formatted with no extra lines for titles or descriptions allowed. File IFL4 is the output file for the field data comparison. This output is identical to the field data comparison table shown in table 2.6, again with abbreviated headings. These two files are opened on approximately lines

1324 and 1337 and closed on lines 1360 and 1362 of subroutine FIELD. Examples of these two files from example FLUME #7 are given in tables A3 and A4.

The program uses labeled COMMON extensively. When only one COMMON block is needed in a subroutine, only that block is used. The user should make sure his or her system allows this. The only other statement that is not standard Fortran IV is on approximately line 2371 of subroutine OUTP1. This statement (EXEC (11)) is used to obtain the time in ITIME (-, -, minutes, hours, Julian date) and the year in IYEAR. No other statements should need to be modified except the FILES statement at the beginning of the main program and Subroutine GAUGE, approximately lines 22 and 1140. These statements have been deleted on the microcomputer version. The G Format descriptor is used on approximately lines 2746 and 2747. This can be changed to an E Format descriptor if G is not available. The G Format descriptor is a combination of the F and E Format descriptors.

Table A1
File J7R (rating table output data) for example FLUME #7

1 2 2

SH1 MM	Q LIT/SEC	FR1	H1/TL	CD	CV	DH MM	Y2-P2 MM	
50.0	.385	.050	.055	.8567	1.003	11.1	38.9	.779
60.0	.612	.060	.066	.8751	1.004	12.4	47.5	.793
70.0	.906	.069	.077	.8881	1.005	13.7	56.2	.805
80.0	1.271	.078	.088	.8978	1.007	14.9	65.0	.814
90.0	1.714	.087	.099	.9049	1.008	16.0	73.8	.823
100.0	2.238	.096	.110	.9108	1.010	17.0	82.7	.830
110.0	2.852	.104	.121	.9165	1.011	18.1	91.7	.837
120.0	3.566	.113	.132	.9233	1.013	19.1	100.5	.842
130.0	4.380	.121	.143	.9292	1.015	20.1	109.5	.846
140.0	5.298	.129	.154	.9343	1.017	21.0	118.5	.851
150.0	6.324	.137	.165	.9387	1.019	21.9	127.5	.855
160.0	7.464	.144	.177	.9426	1.021	22.8	136.6	.859
170.0	8.720	.152	.188	.9461	1.023	23.6	145.7	.863
180.0	10.098	.159	.199	.9492	1.025	24.3	154.8	.866
190.0	11.602	.166	.210	.9520	1.027	25.1	164.0	.869
200.0	13.235	.173	.221	.9545	1.029	25.8	173.2	.873
210.0	15.002	.180	.233	.9568	1.031	26.4	182.5	.876
220.0	16.906	.187	.244	.9589	1.033	27.1	191.7	.879
230.0	18.952	.193	.255	.9608	1.035	27.7	201.0	.881
240.0	21.143	.199	.266	.9625	1.037	28.3	210.3	.884
250.0	23.483	.206	.278	.9644	1.039	28.8	219.6	.886
260.0	25.977	.212	.289	.9659	1.041	29.4	229.0	.889
270.0	28.626	.217	.300	.9673	1.043	29.9	238.3	.891
280.0	31.436	.223	.312	.9685	1.045	30.4	247.7	.893
290.0	34.410	.229	.323	.9697	1.047	30.9	257.1	.896
300.0	37.551	.234	.335	.9709	1.049	31.3	266.5	.898
310.0	40.863	.240	.346	.9720	1.051	31.8	276.0	.900
320.0	44.349	.245	.358	.9730	1.054	32.2	285.4	.901
330.0	48.013	.250	.369	.9739	1.056	32.6	294.9	.903
340.0	51.858	.256	.380	.9748	1.058	33.0	304.4	.905
350.0	55.888	.261	.392	.9757	1.060	33.4	313.8	.907
360.0	60.105	.265	.403	.9765	1.062	33.9	323.6	.908
370.0	64.574	.271	.415	.9781	1.064	34.3	332.8	.910
380.0	69.164	.275	.427	.9786	1.066	34.6	342.2	.911
390.0	73.951	.280	.438	.9791	1.068	35.0	351.5	.913
400.0	78.938	.284	.450	.9795	1.070	35.3	360.9	.914
410.0	84.129	.289	.461	.9800	1.072	35.7	370.7	.915
420.0	89.527	.293	.473	.9802	1.074	36.1	380.2	.916
430.0	95.134	.297	.484	.9806	1.075	36.4	389.8	.918
440.0	100.955	.302	.496	.9811	1.077	36.7	399.3	.919

Table A2
File J76 (wall gauge output data) for example FLUME #7

FLUME #7

1	2	2

Q LIT/SEC	SHS MM
10.0000	207.0242
20.0000	271.1600
30.0000	317.4500
40.0000	354.9529
50.0000	387.0280
60.0000	415.3483
70.0000	440.7703
80.0000	464.2088
90.0000	485.8922
100.0000	506.1260

Table A3
File JRD7 (field data comparison input data) for example FLUME #7

56.4	0.532
57.9	0.569
85.0	1.495
151.5	6.56
170.1	8.72
189.0	11.31
189.9	11.58
200.0	13.47
221.0	17.24
257.0	25.2
265.0	26.9
328.0	47.2
329.0	47.4
338.0	50.8
355.0	57.7
377.0	67.0
399.0	77.7
409.0	82.7
411.0	84.2

Table A4
File J7F (field data comparison output data) from example FLUME #7

1 2 SH1 MM	2 MEASURED Q LIT/SEC	MODEL Q LIT/SEC	IDEAL Q LIT/SEC	MODEL H1/L	MEASURED CD	MODEL CD	PERCENT DIFFERENCE
56.4	.532	.523	.602	.0618	.8843	.8692	-1.73
57.9	.569	.559	.641	.0634	.8872	.8718	-1.77
85.0	1.495	1.482	1.645	.0933	.9091	.9015	-.85
151.5	6.560	6.488	6.907	.1670	.9498	.9394	-1.11
170.1	8.720	8.733	9.230	.1878	.9447	.9461	.15
189.0	11.310	11.446	12.026	.2090	.9404	.9517	1.19
189.9	11.580	11.586	12.171	.2100	.9515	.9520	.05
200.0	13.470	13.235	13.866	.2213	.9715	.9545	-1.78
221.0	17.240	17.104	17.834	.2450	.9667	.9591	-.79
257.0	25.200	25.212	26.115	.2857	.9650	.9654	.05
265.0	26.900	27.281	28.225	.2948	.9531	.9666	1.40
328.0	47.200	47.265	48.541	.3667	.9724	.9737	.14
329.0	47.400	47.638	48.919	.3678	.9689	.9738	.50
338.0	50.800	51.074	52.404	.3782	.9694	.9746	.54
355.0	57.700	57.974	59.395	.3977	.9715	.9761	.47
377.0	67.000	67.767	69.257	.4231	.9674	.9785	1.13
399.0	77.700	78.430	80.072	.4485	.9704	.9795	.93
409.0	82.700	83.601	85.312	.4601	.9694	.9799	1.08
411.0	84.200	84.659	86.385	.4624	.9747	.9800	.54
440.0	100.100	100.955	102.903	.4960	.9728	.9811	.85

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